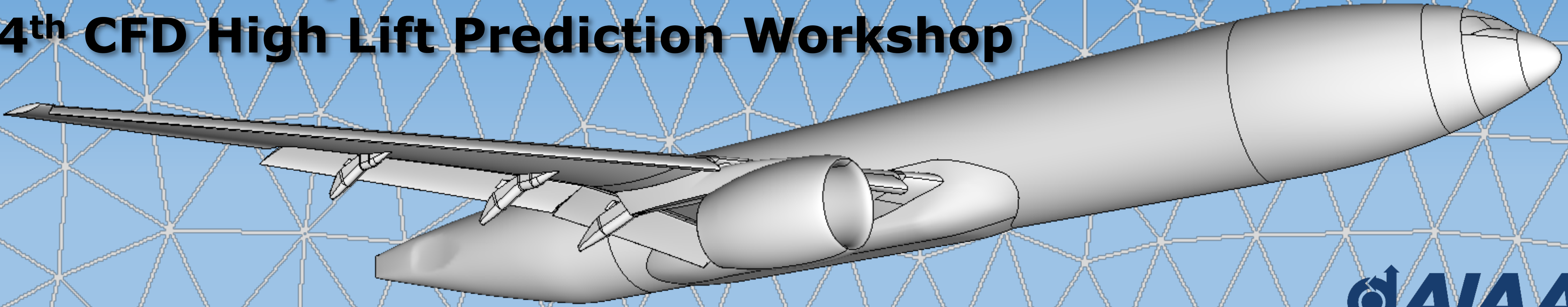
3rd Geometry and Mesh Generation Workshop
4th CFD High Lift Prediction Workshop



HO-TFG Meshing & Solution

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Steve Karman (Oak Ridge National Laboratory)

Terminology

- Mesh order is referenced by the polynomial degree of the basis function
  - Q1 (linear, e.g. standard mesh)
  - Q2 (quadratic)
  - Q3 (cubic)
  - Q4 (quartic)

- Finite Element solution order is referenced using a similar convention
  - P1 is 2nd order solution
  - P2 is 3rd order solution

- P1Q2-FV and P2Q2-FV are 2nd and 3rd-order Finite-Volume discretizations that couple the solution on curved Q2 Primal and Dual meshes

Demographics Mesh Generation

TFG ID/Name
G = Geometry
R = RANS
A = Adaptation
H = High-order
L = Hybrid RANS/LES
W = WMLES/LB

TFG Name	HO
Number of Active Participants (current)	~12
Number of Observers (current)	~10

Group Submissions Received	Members (Org)	Tools Used (Geom/Grid/Solver), by name	Participation
H-001	ORNL (Pointwise)	Pointwise, HP_CurveMesh	HLCRM (Q2), Juncture Flow Model (Q2)
H-003	GridPro	GridPro	2D-HLCRM (Q2), Juncture Flow Model (Q2)
H-006	INRIA	ho-feflo.a	HLCRM (Q2)
H-019	Barcelona Sup. Cent.	Pointwise, ParCur	HLCRM (Q2)

Demographics Solver

TFG Name	HO
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SHAPING THE FUTURE OF AEROSPACE

Group Submissions Received	Members (Org)	Tools Used (Geom/Grid/Solver), by name	Participation
H-004	MIT	SANS	RANS-SA: 2D-HLCRM(Q2) P1-P2 SUPG/VMSD Adapt
H-005	ORNL, UTK, DoD CREATE-AV	COFFE	RANS-SA: 2D-HLCRM(Q2) P1-P2 SUPG
H-012	ONERA / DAAA	HO_DualMaker(Q2), Nextflow_ITW	URANS-SA: 2D-HLCRM(Q1) P2, HLCRM(Q2) P1
H-023*	Boeing	GGNS	RANS-SA: HLCRM(Q2) P2
H-013	Princeton	maDG	ILES: HLCRM(Q1) P1-P3 DG
W-047	U Kansas	HpMusic	WMLES: HLCRM(Q2) P2 Flux Reconstruction
H-021	Tecplot	Tecplot	Solution visualization for high-order FEM

*Late submission

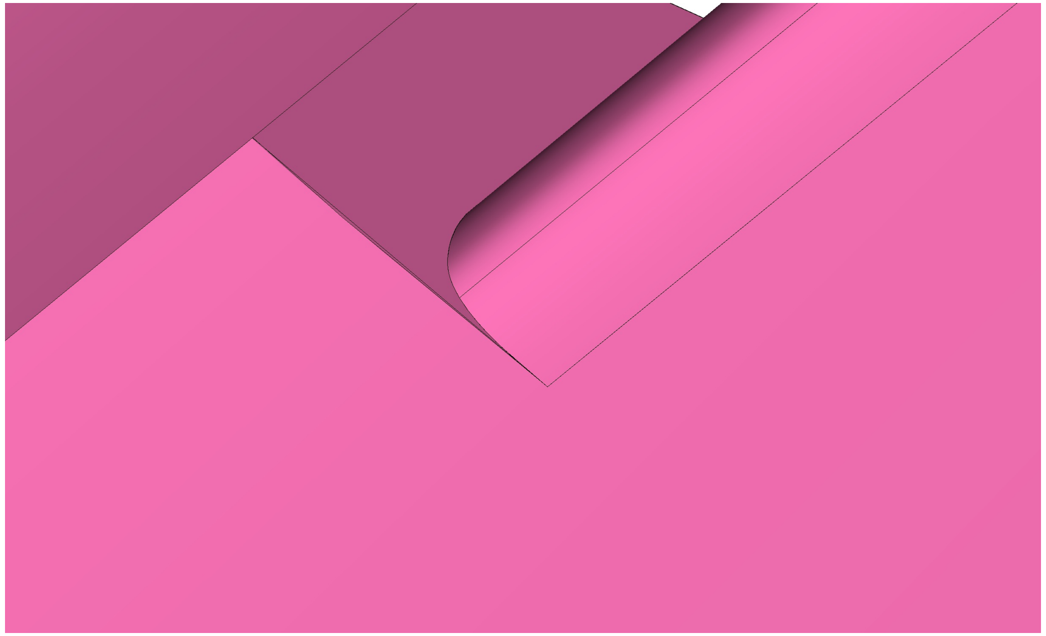
Key Questions

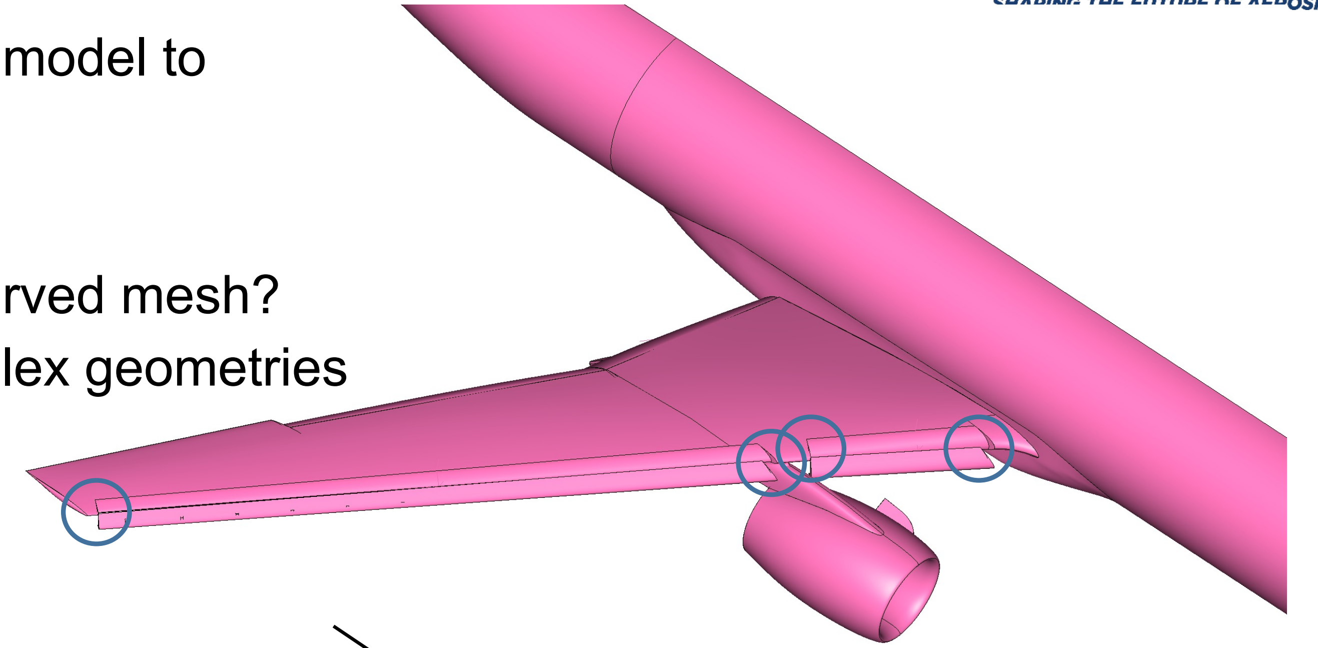
#	Key Question	By Which Groups (PID)	Adequately answered with supporting evidence?
1	Can 3D curved Q2/Q3 meshes be generated for the HL-CRM?	H-001, H-006, H-019	Yes
3	What mesh quality metrics are used to evaluate high order meshes?	H-001, H-019	Yes
4	How well do the curved meshes conform to the actual geometry?	H-001, H-019	Yes
5	Can high-order FEM/FV schemes be used with the HL-CRM configuration?	H-012, H-013, H-023	Partially
6	What are the Y+ normal distance requirement for LES/WMLES with high order finite element schemes?	H-013	Partially

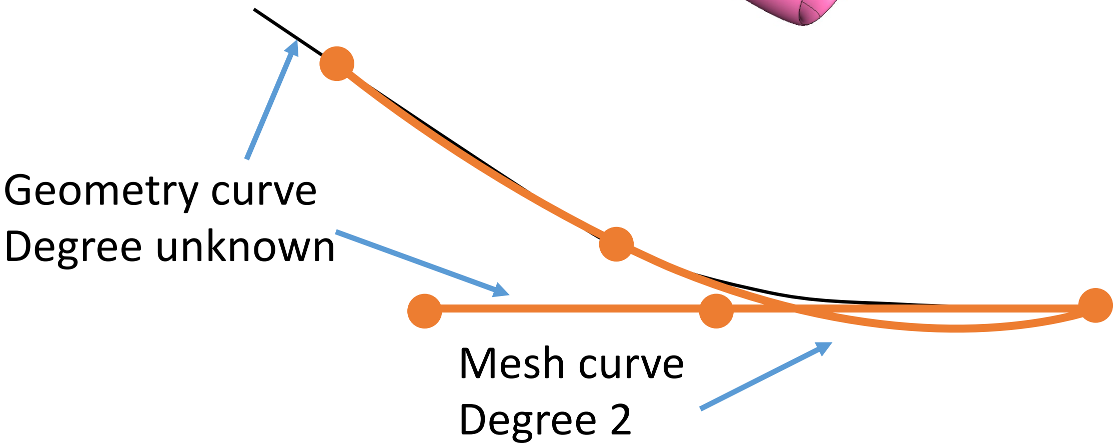
Geometry/Meshing Trouble Spots

- Pinch points were “fixed” in the geometry model to eliminate cross-over.
  - Curving process (Q2) still had issues.

- Should we modify the geometry or the curved mesh?
- Virtual geometry and quilts help for complex geometries







Meshing Findings/Lessons Learned

- A supplemental HO Mesh Generation Guidelines document was created that extended the meshing parameter sets in the coarser direction, adding AA, AAA and AAAA and eliminated E and F from the tables.

- Initial AAAA meshes were generated and curved using Pointwise
  - Most participants lacked computer resources to run these meshes

- A new series was created (Coarse, Medium, Fine and Extra Fine)
  - The coarsest mesh was the smallest mesh possible, maintaining geometry integrity.

- Participants experimenting with HO-WMLES algorithms.
  - Curved meshes generated with increased normal distances (Y+ values of 10, 50, 100, 200, 800 based on Pointwise Y+ calculator)

Meshing Findings/Lessons Learned

- Curved 2D meshes were generated with H-003 and H-002

- H-001 and H-003 generated curved meshes for the Juncture Flow Model case (no solutions were attempted, a meshing-only exercise).

- H-001 and H-019 (CRM-HL)
  - Linear meshes were generated and curved

- H-006 (CRM-HL)
  - Started with the Pointwise linear meshes and generated curved meshes

- H-012 (CRM-HL)
  - High-order Dual meshes generated with HO_DualMaker starting with Pointwise Q2 meshes

Meshing Findings/Lessons Learned

- The most importance quality metric is the Jacobian, which can vary within a high-order element
  - The curving with viscous clustered meshes must ensure positive Jacobians (mesh validity)
  - Scaled Jacobian and relative shape distortion are used to check the mesh quality

- Shape conformity is an important metric that measures the error between the curved mesh and the geometry shape

- Finer mesh around nacelle on Q2 Coarse mesh greatly improved WMLES solution

Shape Conformity

H-001: Medium mesh. Selected body components. Y+ ~ 1

Body	Max. Error		Avg. Error	
	Q1	Q2	Q1	Q2
Fuselage	1.27	0.21	0.11	2.6e-3
Nacelle	0.37	4.9e-2	0.023	4.6-4
Wing	0.26	3.6e-2	5.7e-3	1.9e-4

H-019: Medium mesh. Full vehicle. Y+ ~100

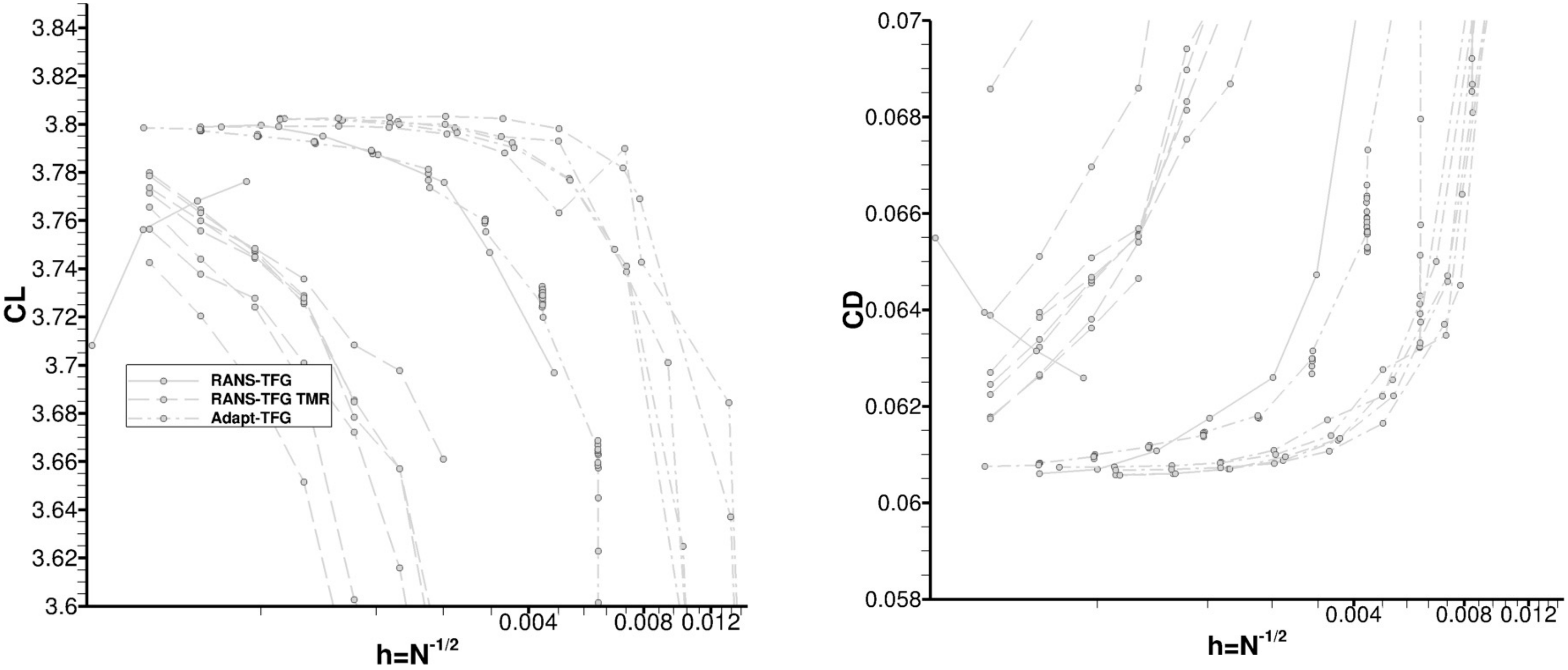
Body	Max. Error			Avg. Error		
	Q1	Q2	Q3	Q1	Q2	Q3
Full Vehicle	1.48	0.25	0.12	0.1	9.8e-4	2.9e-4

High-Order Case3 RANS-SA

- **H-005**: FEM implicit steady RANS
  - GridPro(P1Q1, P2Q2), and TMR(P1Q1) meshes
- **H-004**: (MIT): FEM implicit steady RANS
  - GridPro(Q2), TMR(Q1), and Adapted(Q3) meshes with P1 and P2
- **A-013**: (MIT): FEM implicit steady RANS
  - TMR(Q1), and Adapted(Q1), meshes with P1
- **H-012**: FV time-implicit URANS, explicit pseudo-time solver
  - GridPro (Q2) P2
  - Time averaged solutions for lift and drag

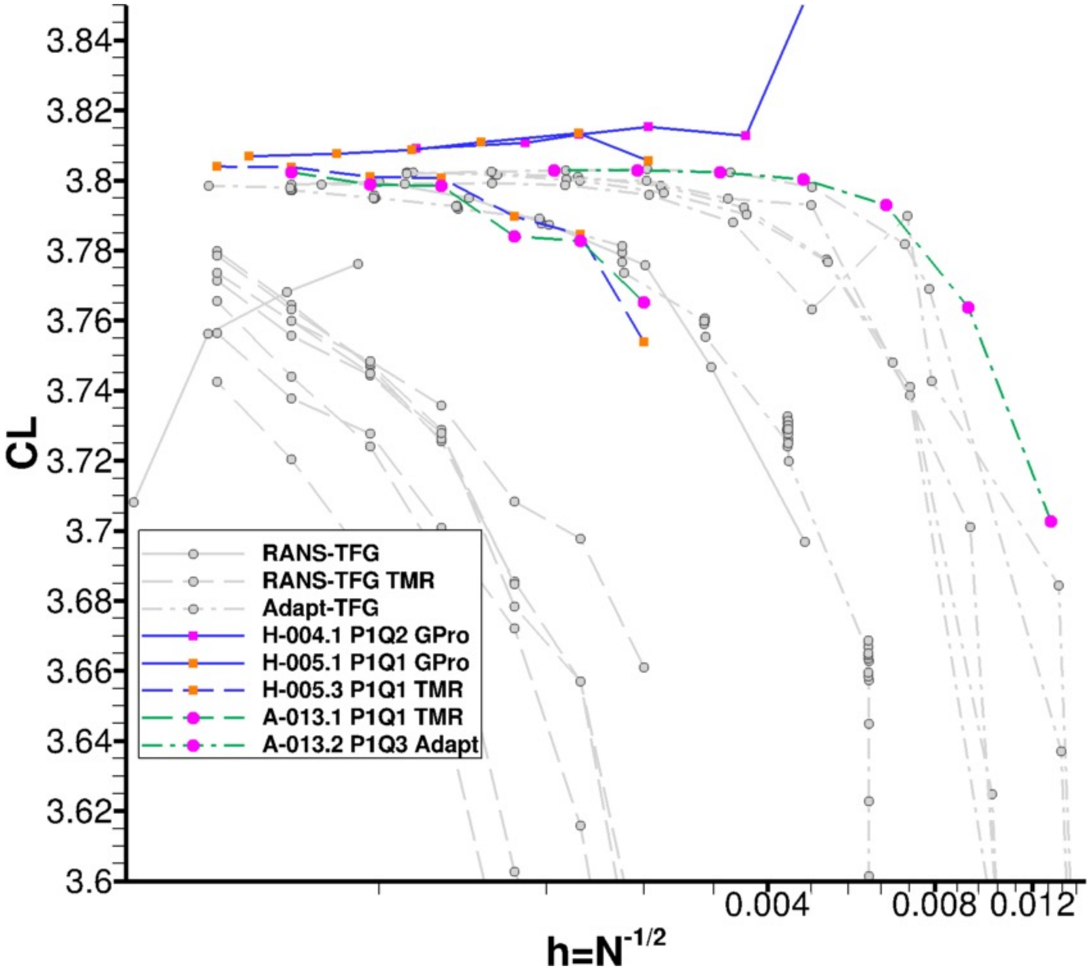
Basic CFD Results Case3

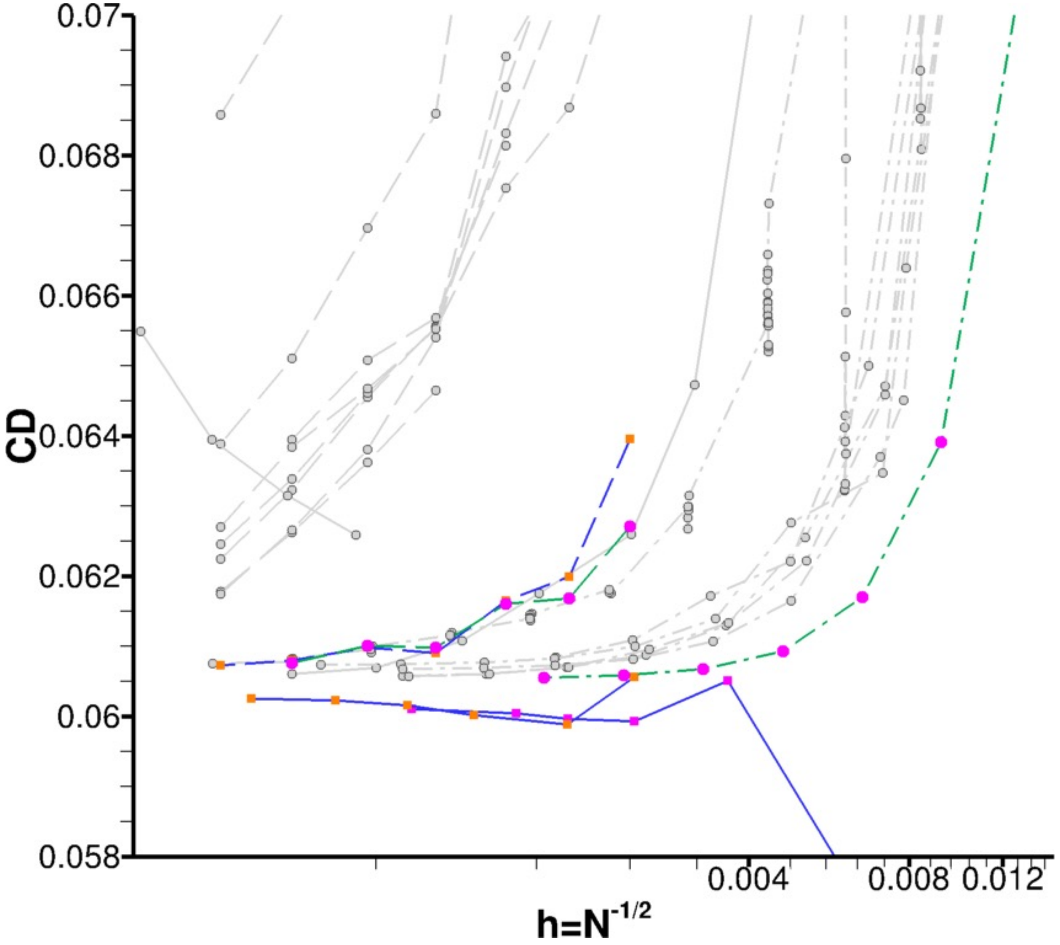
2D CRM Airfoil Lift and drag convergence with degree of freedom refinement: RANS-SA



Basic CFD Results Case3

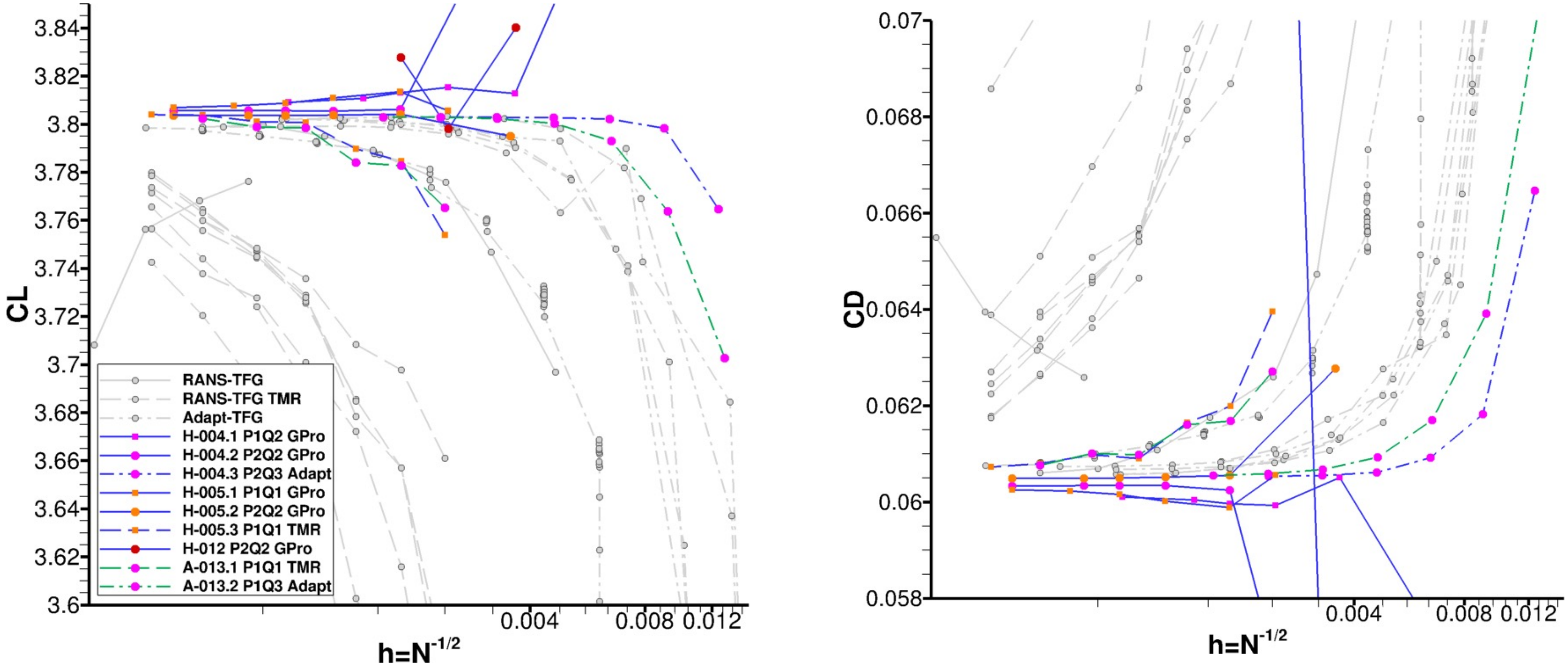
2D CRM Airfoil Lift and drag convergence with degree of freedom refinement: RANS-SA





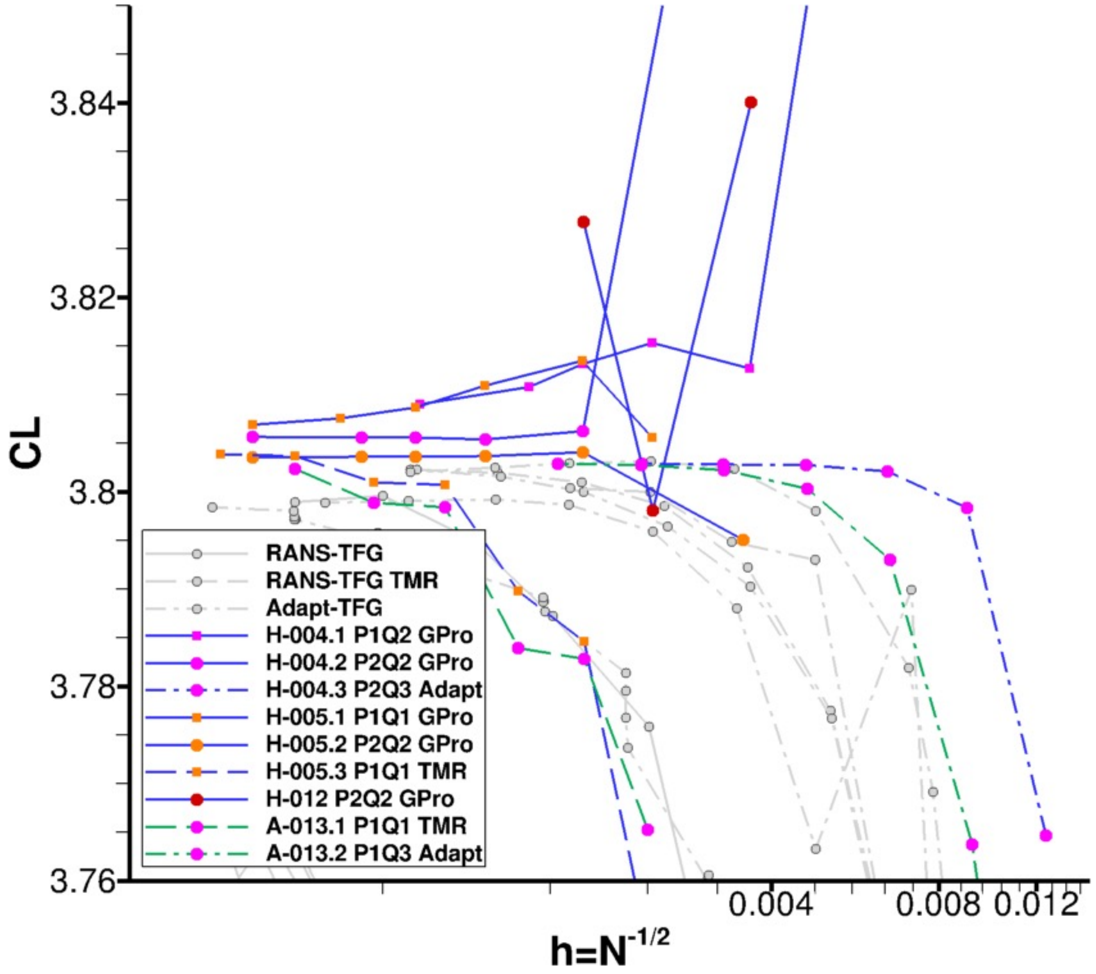
Basic CFD Results Case3

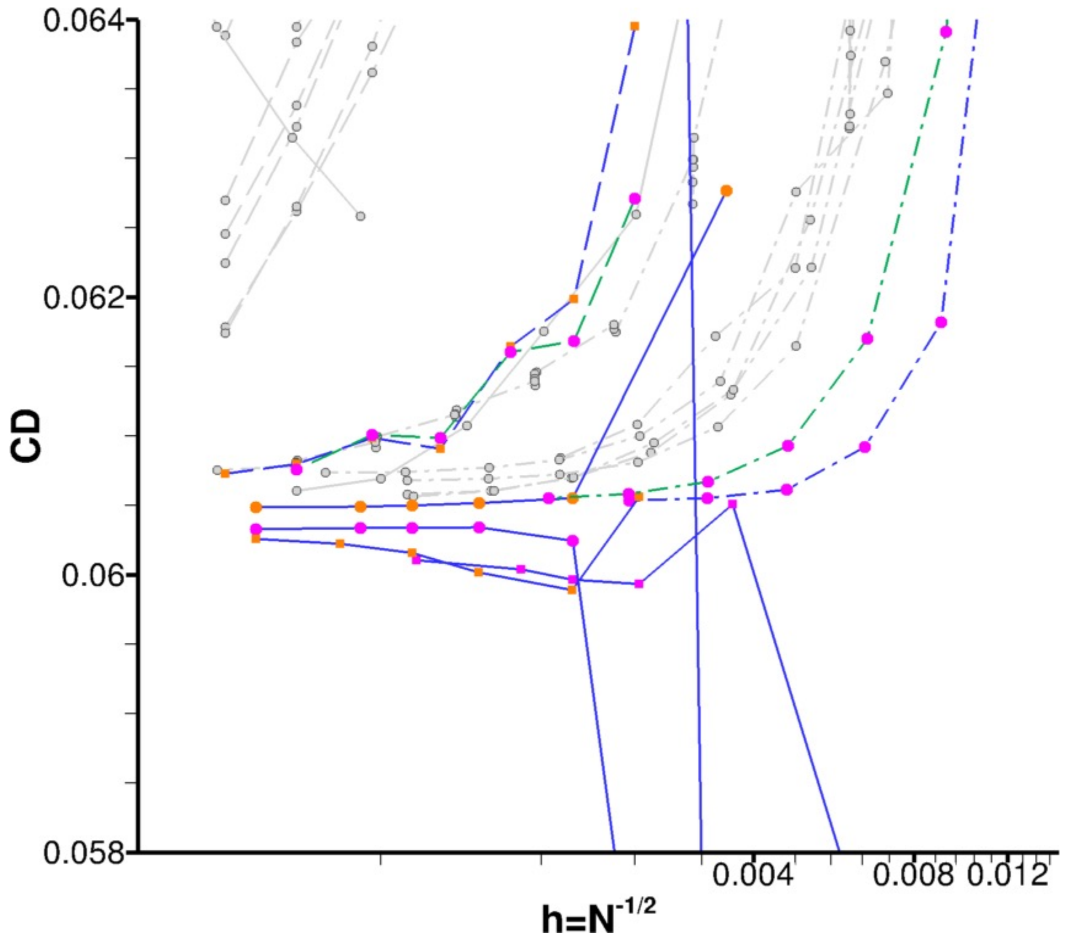
2D CRM Airfoil Lift and drag convergence with degree of freedom refinement: RANS-SA



Basic CFD Results Case3

2D CRM Airfoil Lift and drag convergence with degree of freedom refinement: RANS-SA





High-Order Case1b and Case2a

H-012

- P2 FV, k2 reconstruction
- RANS-SA
- Explicit time stepping
- Q2 mesh 2 to 21M mixed
  Pointwise Coarse to Medium
  Various Y+ : 100 to 800
- Coupled solver :
  - cell-center + cell-vertex (2G)
  - cell-center + cell-vertex + cell-edge (3G)
  - cell-center + cell-vertex + cell-edge + cell-face (4G)

H-013

- DG method in space
- BDF2 with GMRES
- No wall model
- Implicit LES (dt = 4.5e-5)
- Q1 mesh 3M tet
  (Pointwise Y+ = 100)
  - P1 12M DOF
  - P2 30M DOF
  - P3 60M DOF
- Re 0.5×10^6

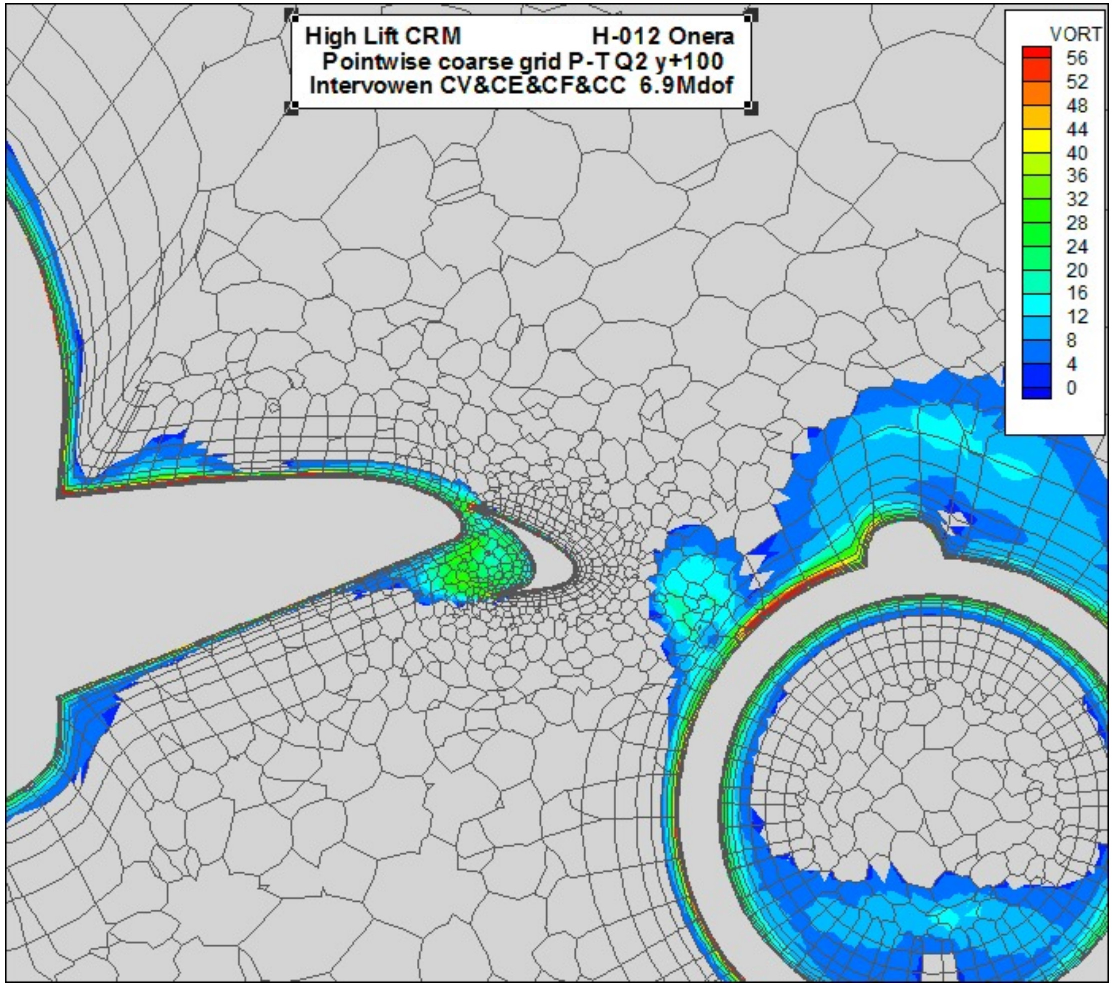
W-047

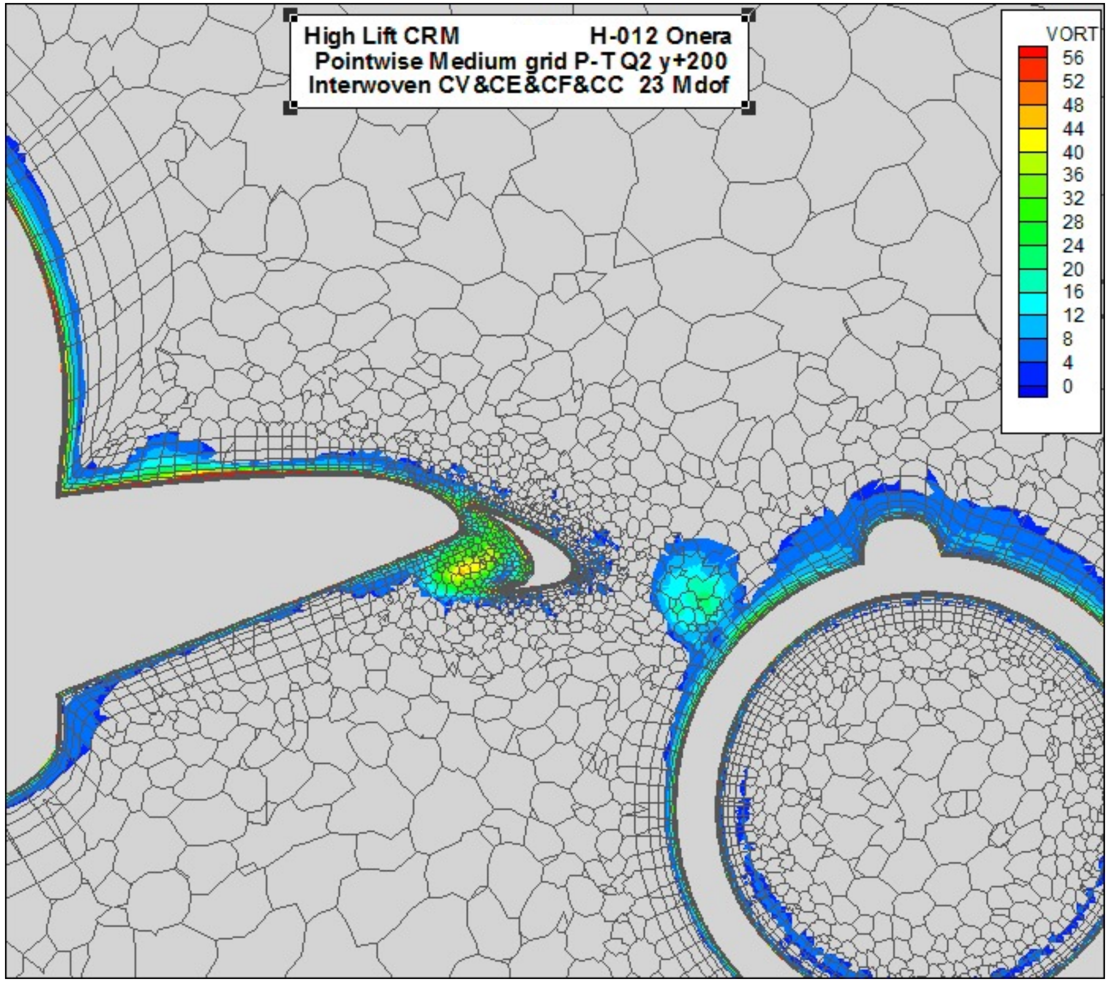
- P1 and P2 FR/CPR
- BDF2 with GMRES
- Equilibrium wall-model
- Implicit LES
- Q2 mesh 1.02M mixed
  (Pointwise Y+ = 800)
  - P1 4.8 M DOF
  - P2 13.2 M DOF
  - Equivalent Y+ ~ 200-260 near the wall (~7mm)

H-023

- P2 SUPG
- RANS SA-neg
- Fully implicit GMRES
- Q2 mesh 6M tet (Pointwise Y+ = 200)
  - P2 7.8M DOF

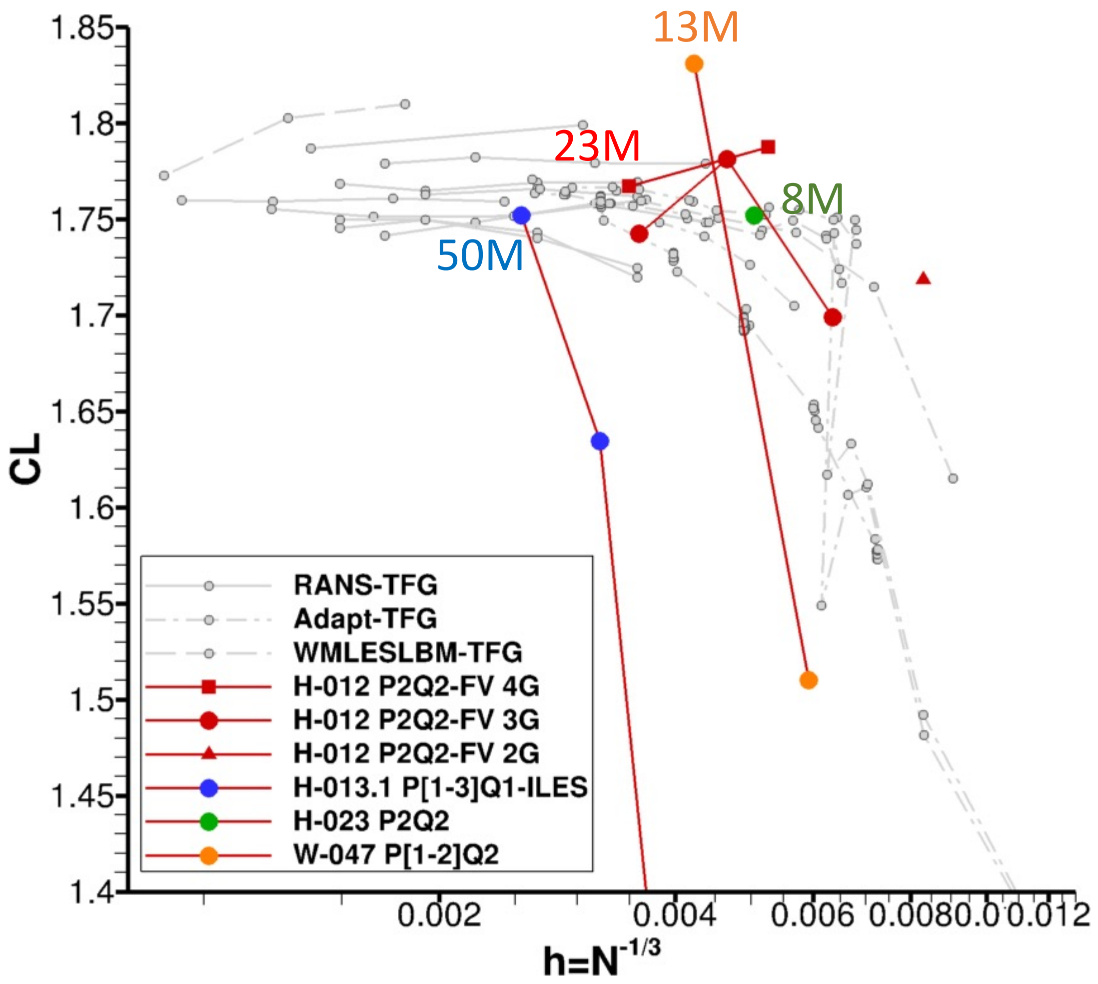
H-012: URANS (7.05 AoA) View 11 on Cell-Vertex Grid Refinement Effect

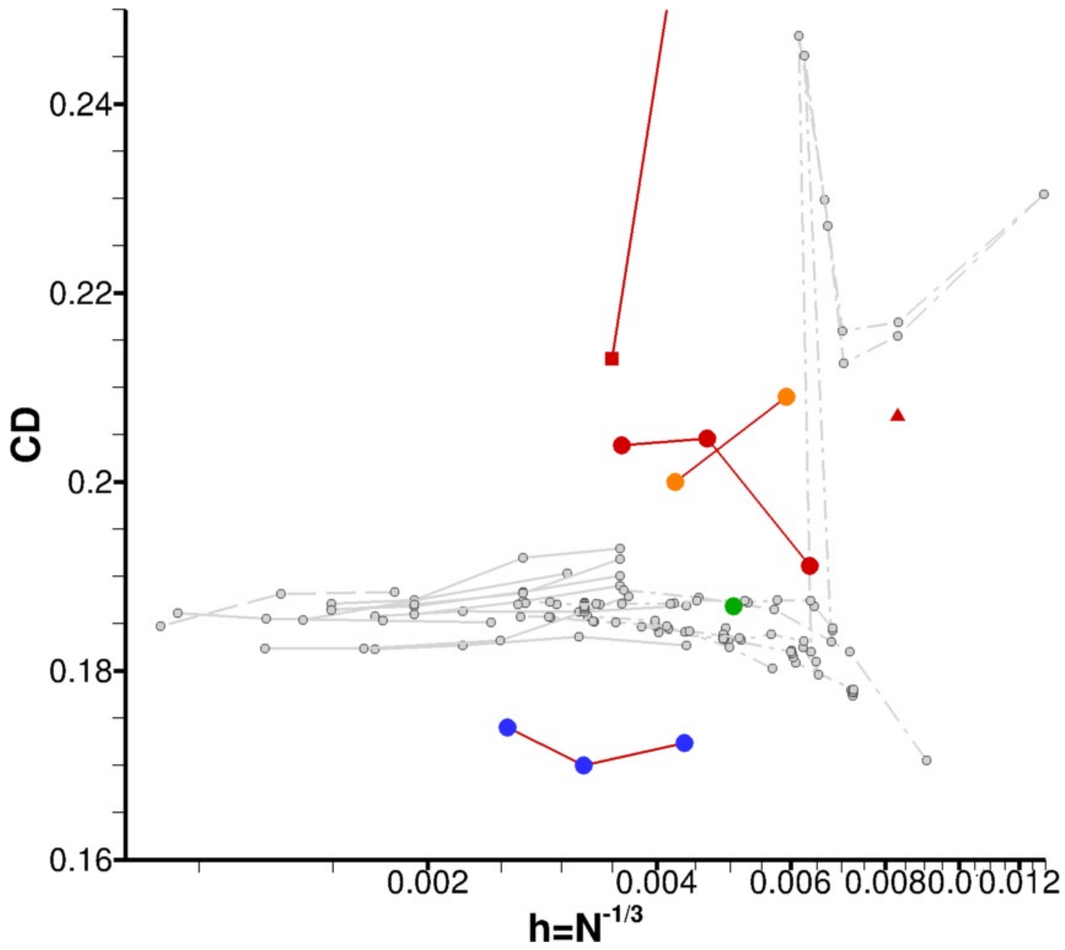




Basic CFD Results Case1b

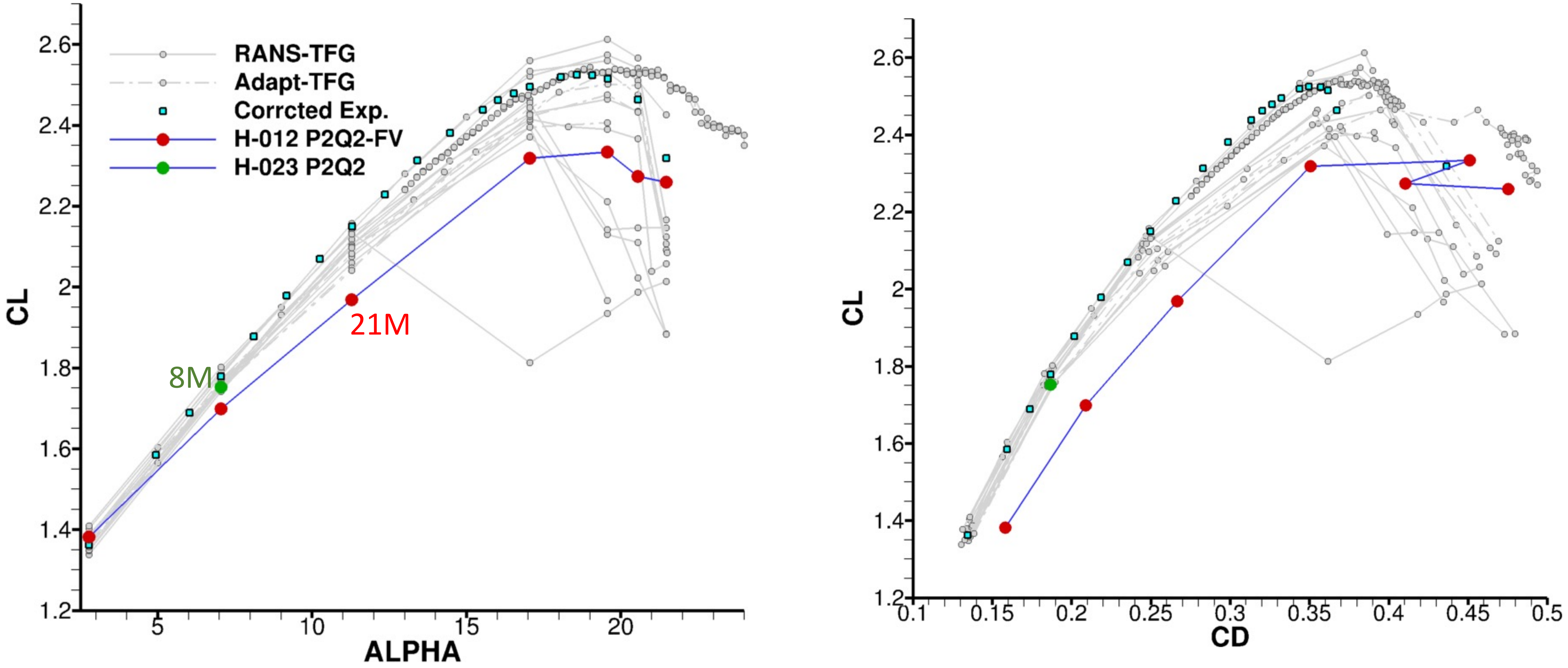
Lift and drag convergence with degree of freedom refinement





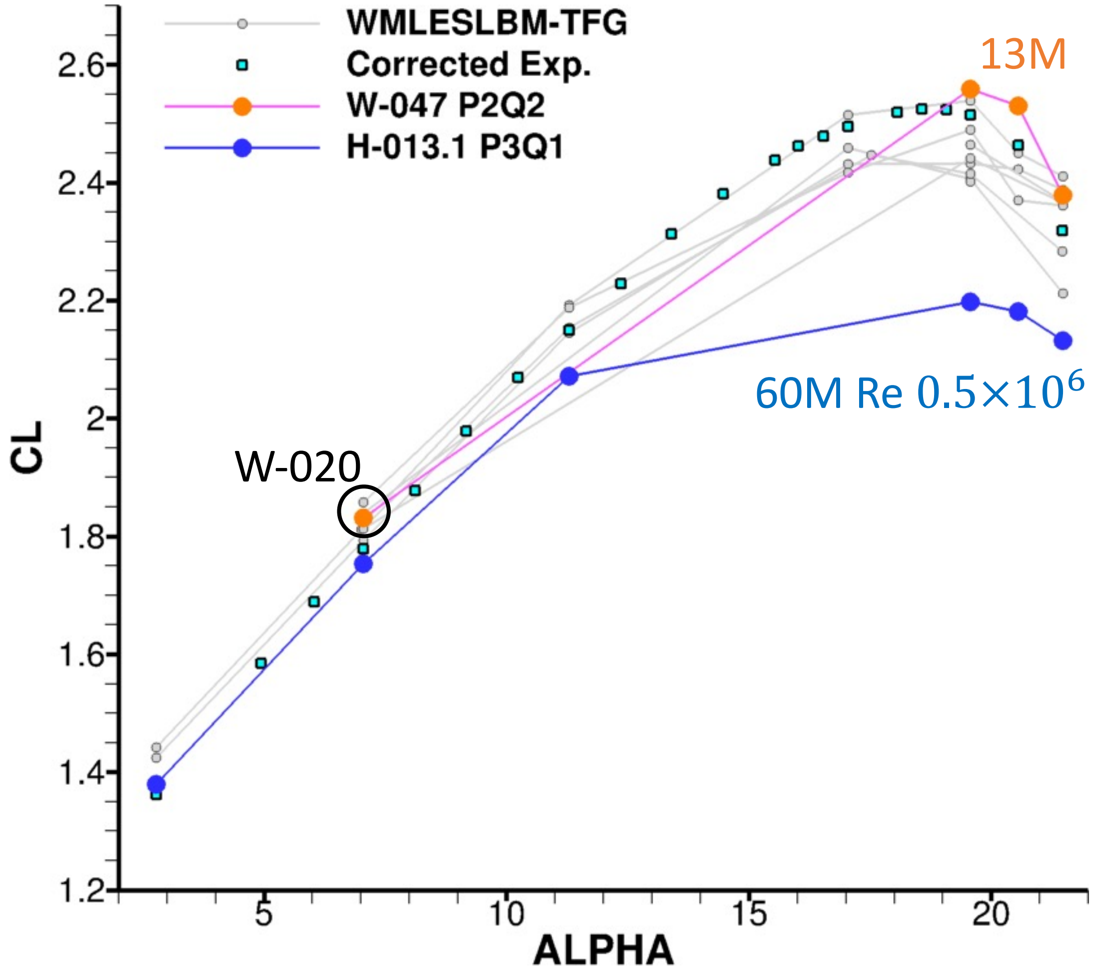
Basic CFD Results Case2a

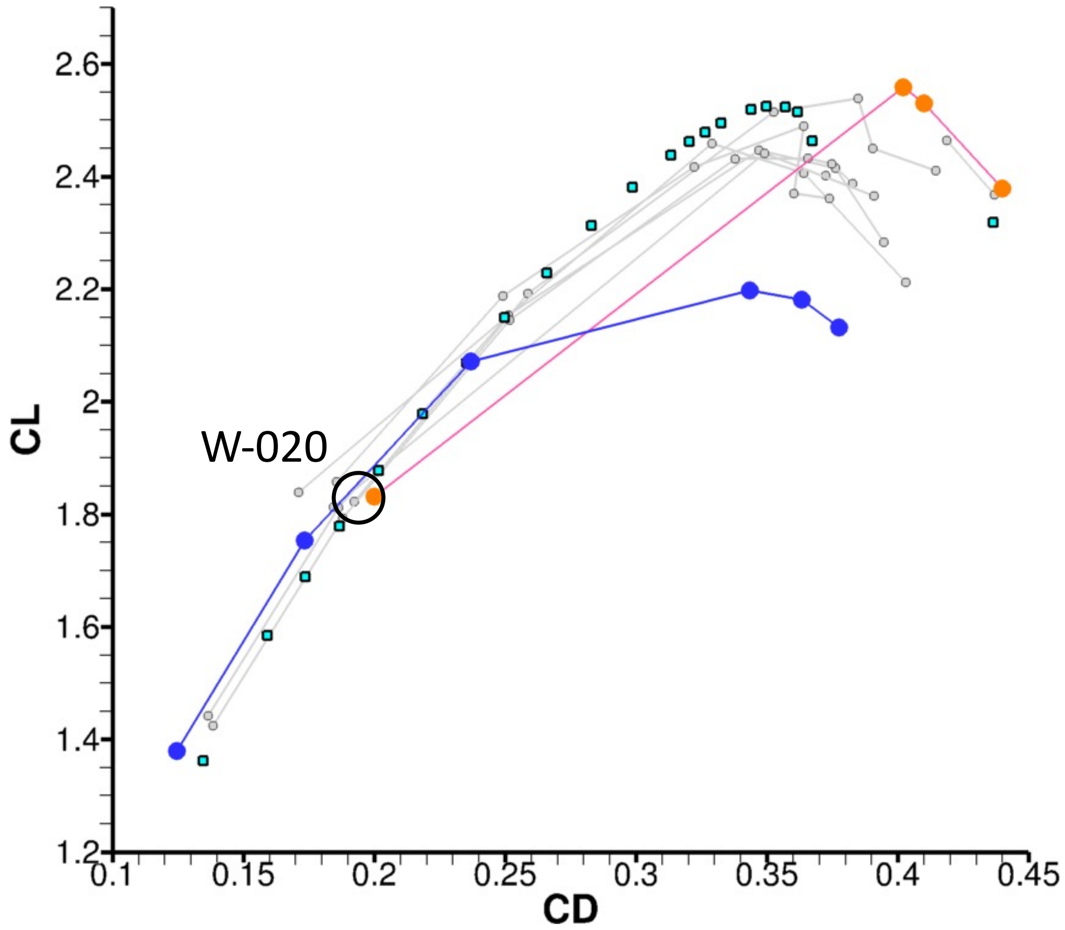
Lift curve (CL-α), drag polar (CL-CD): RANS-SA



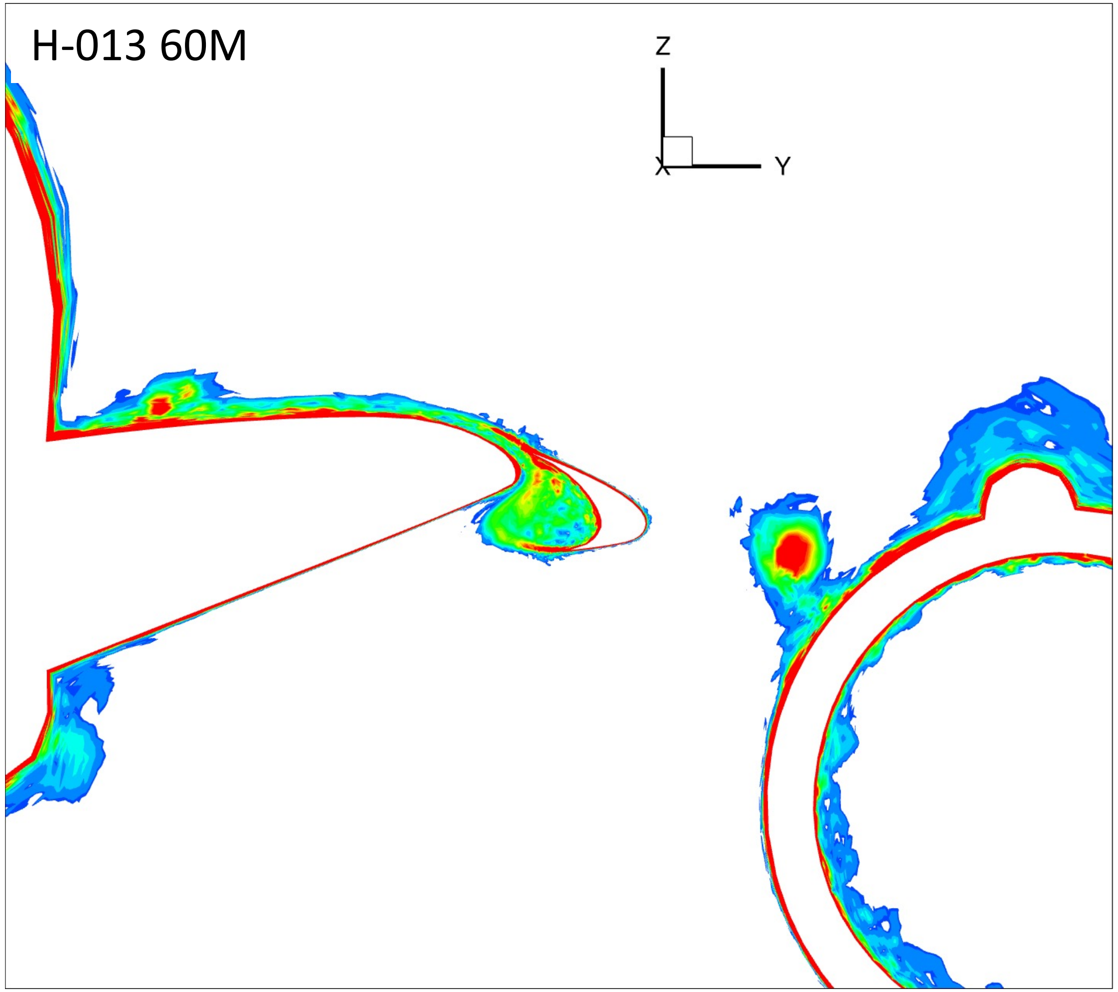
Basic CFD Results Case2a

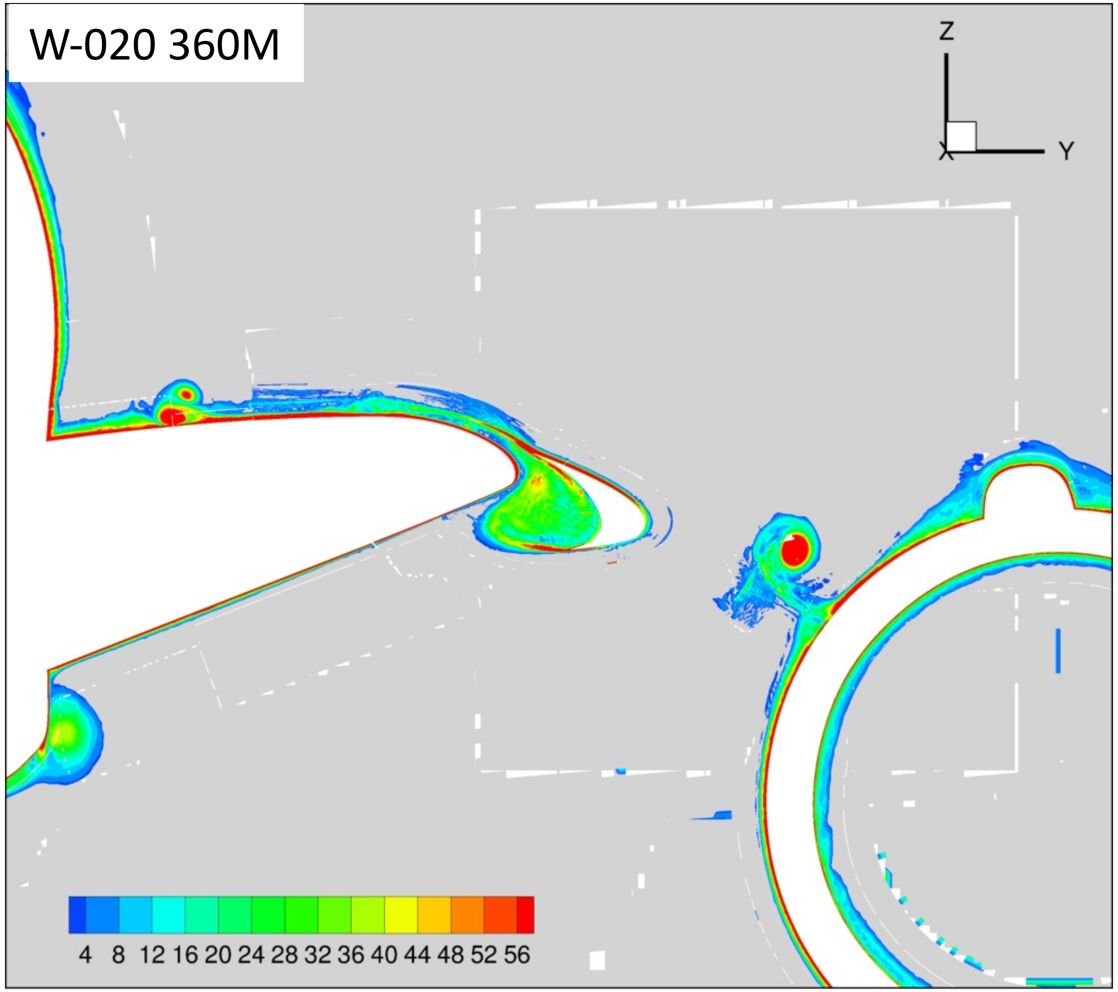
Lift curve (CL-α), drag polar (CL-CD): LES



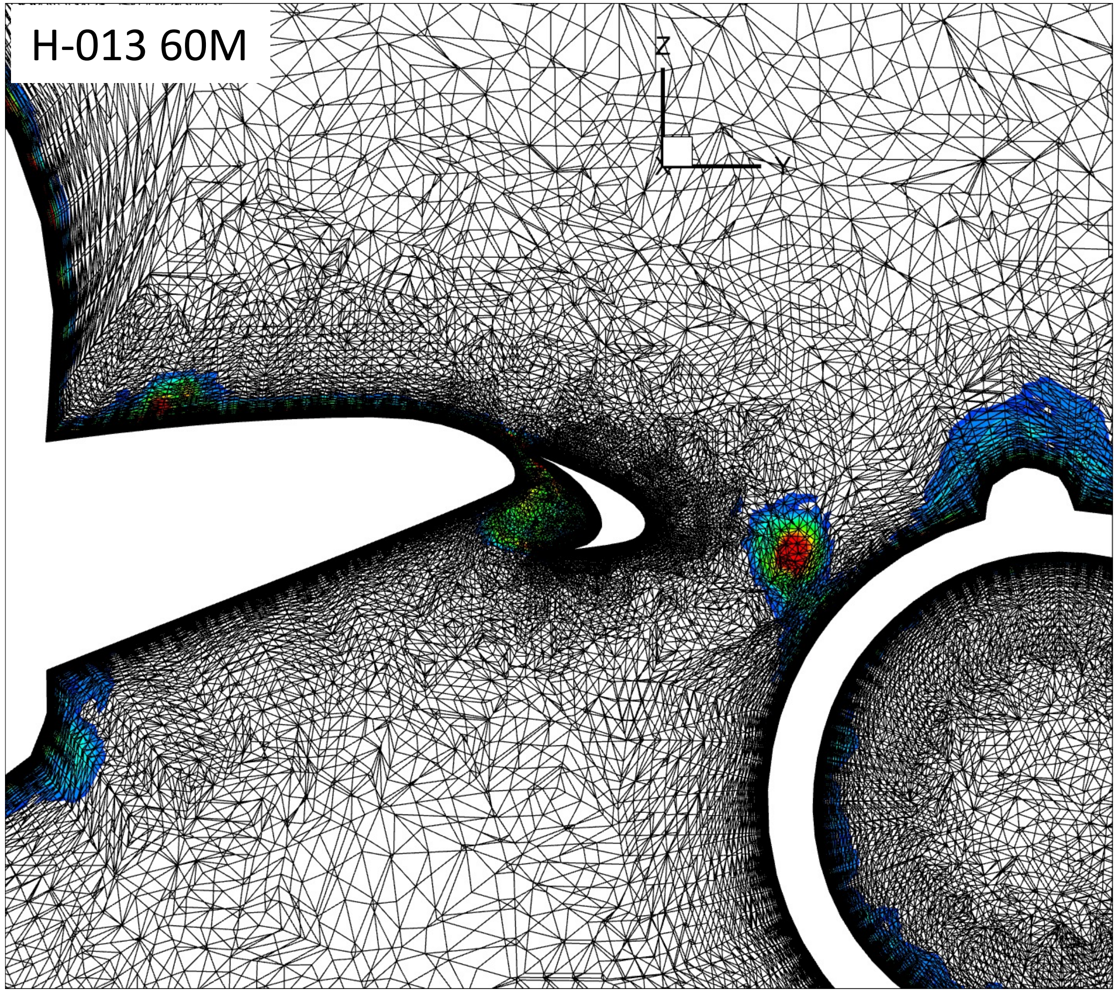


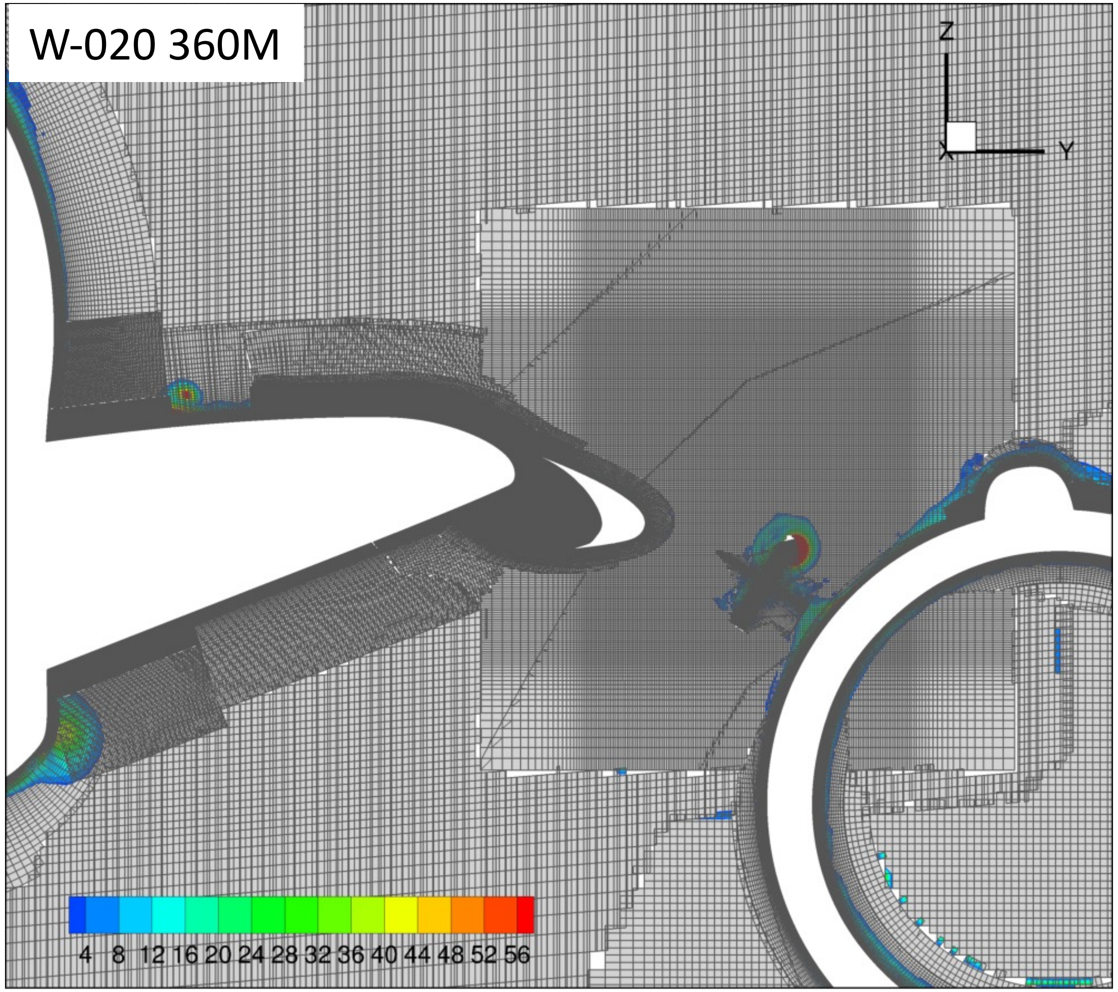
ILES (7.05 AoA) View 11



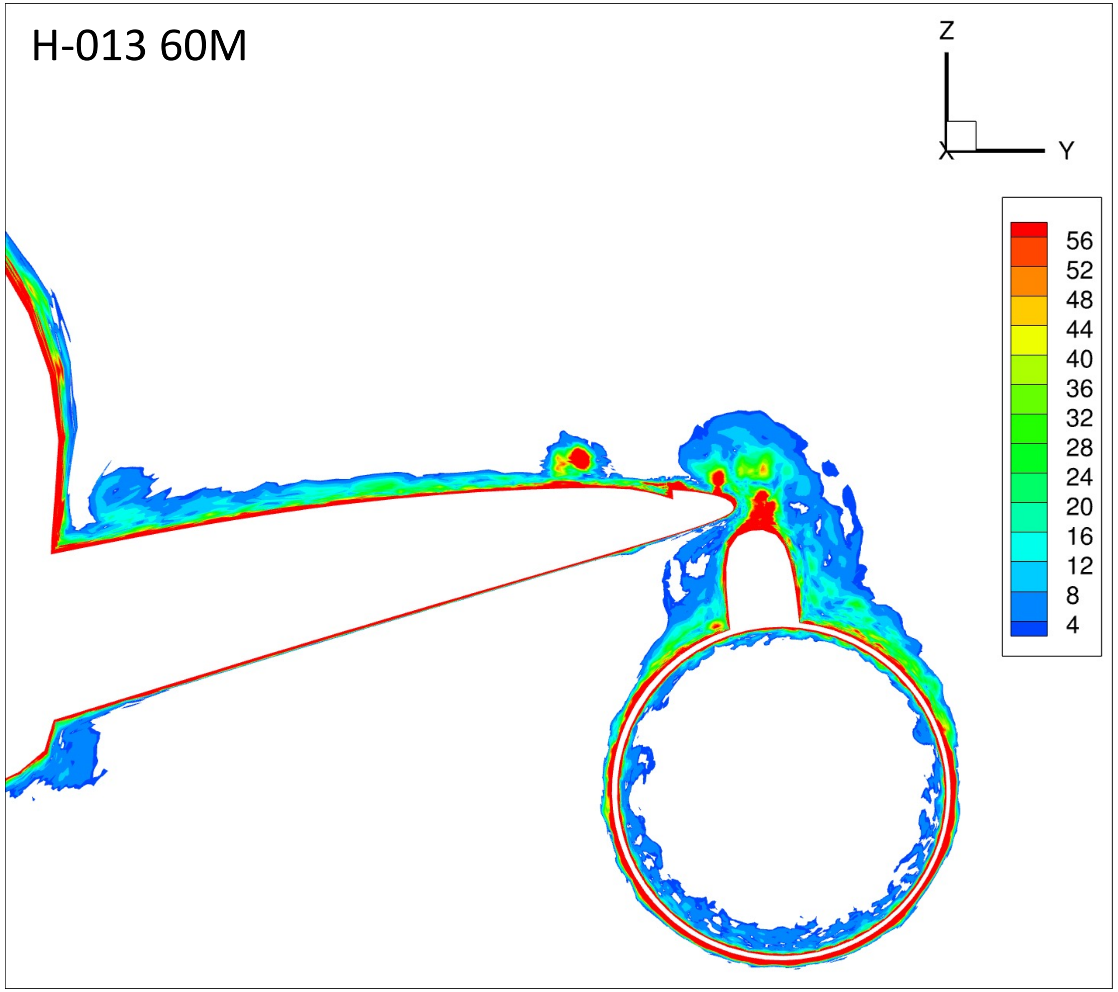


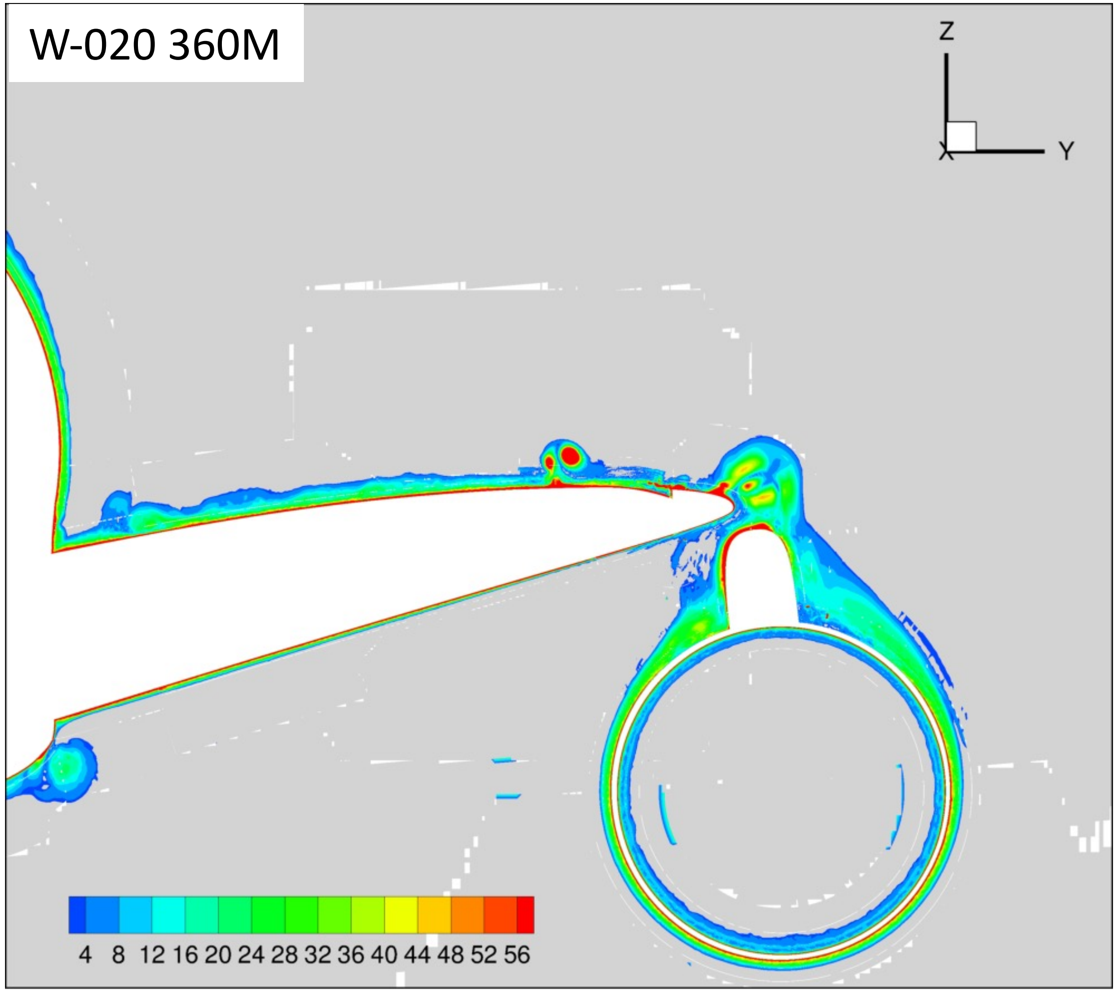
ILES (7.05 AoA) View 11





ILES (7.05 AoA) View 12





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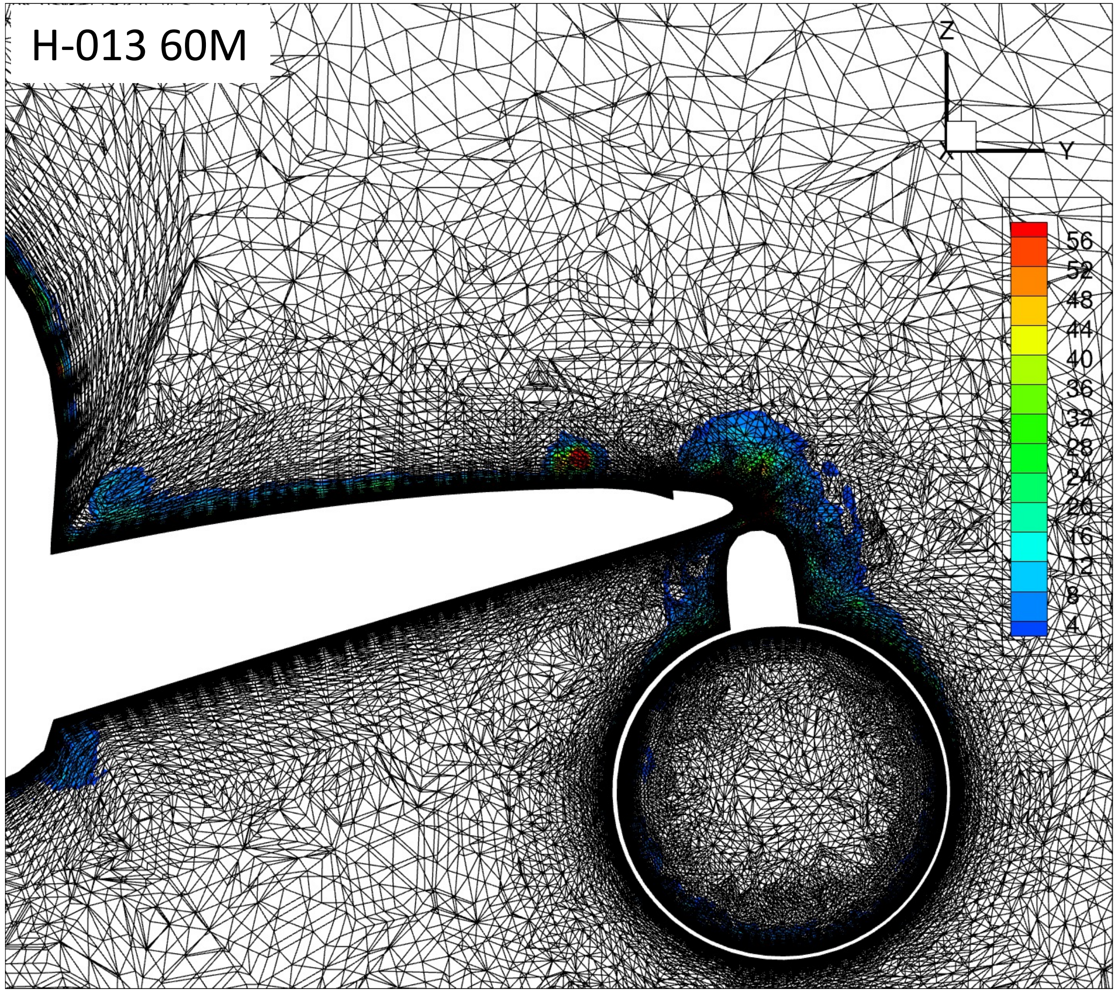

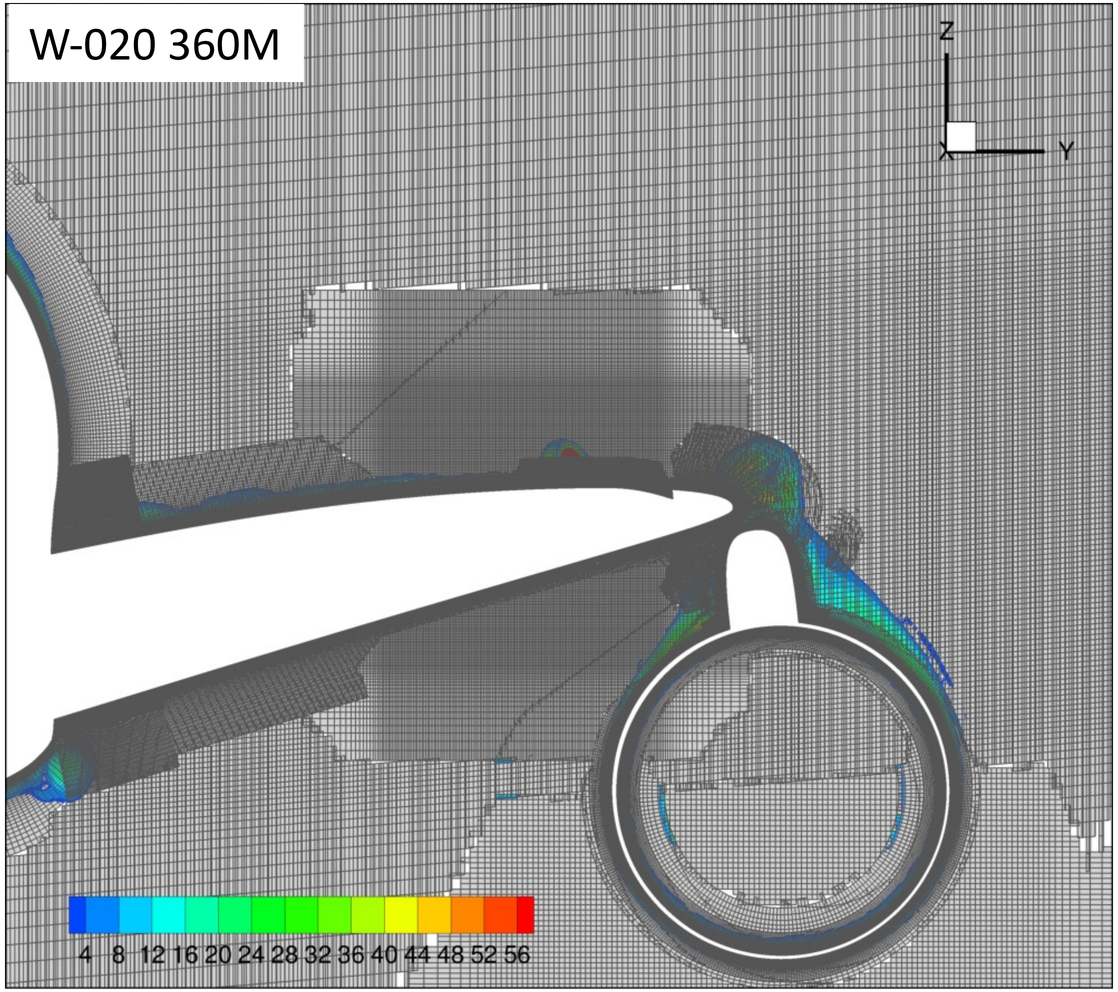

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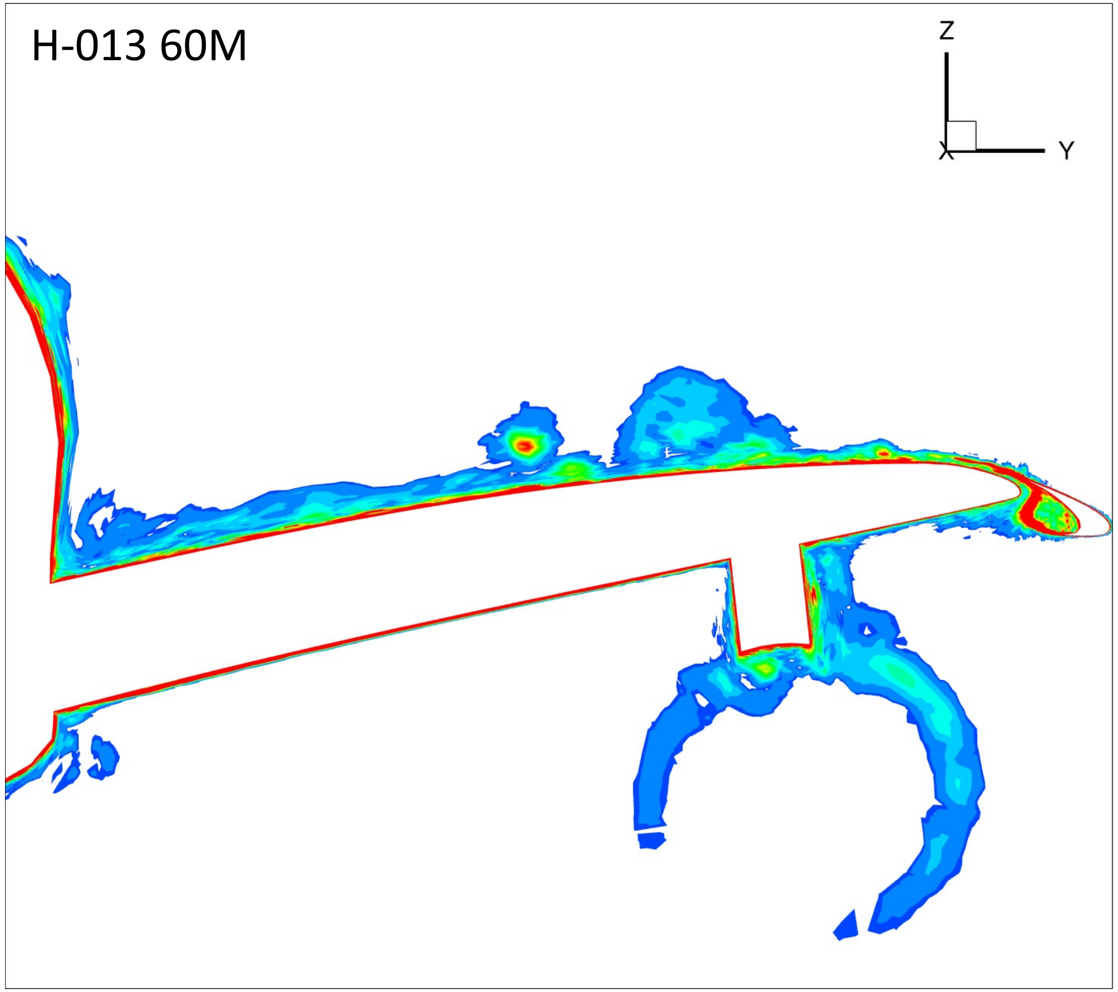

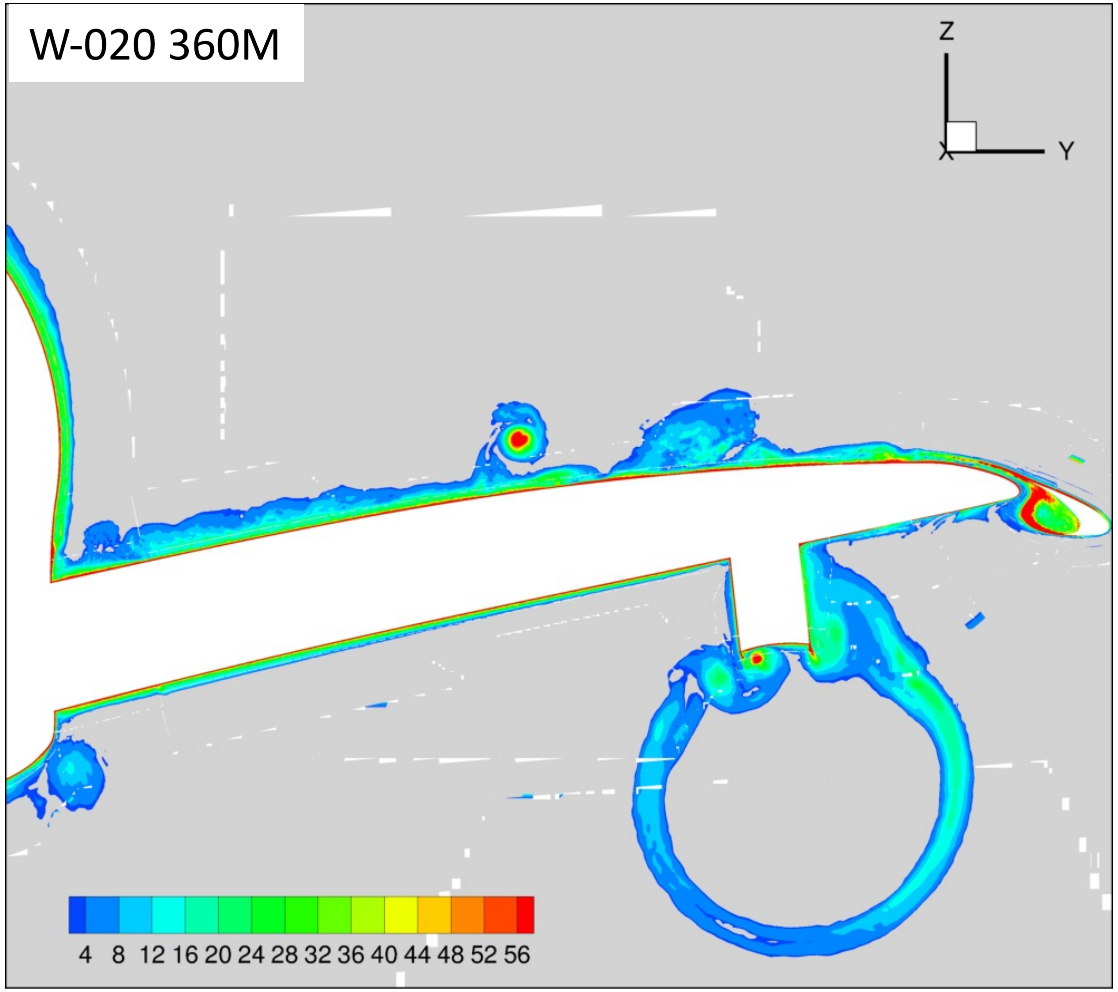

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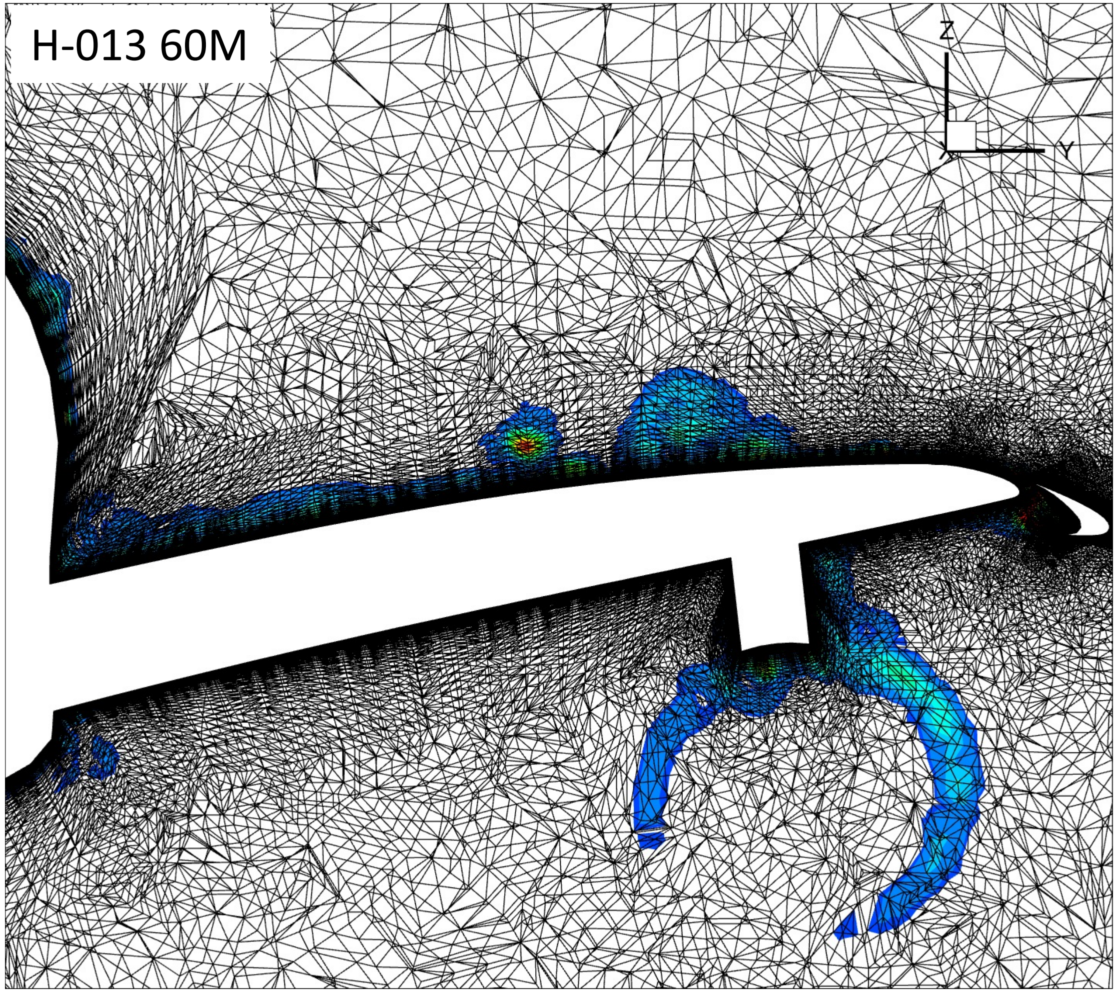
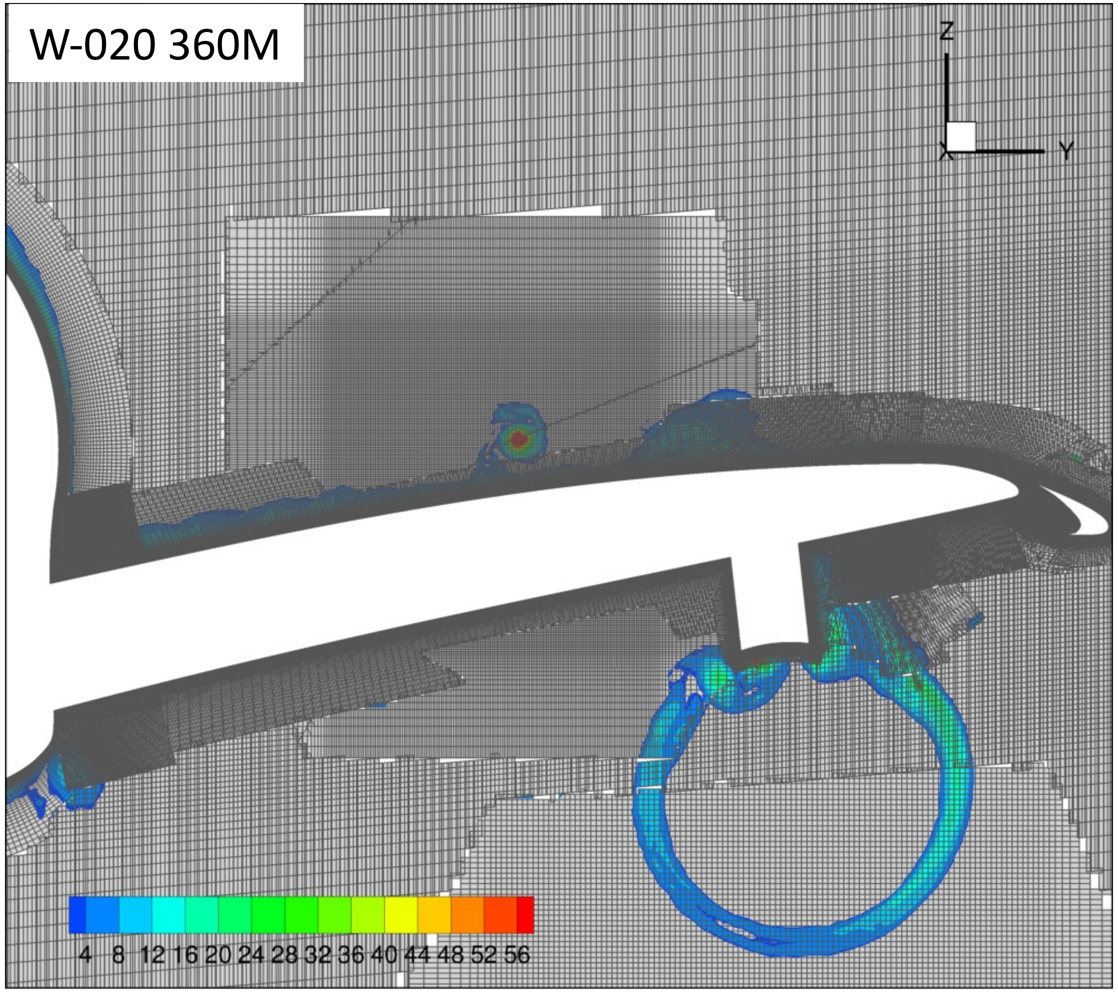
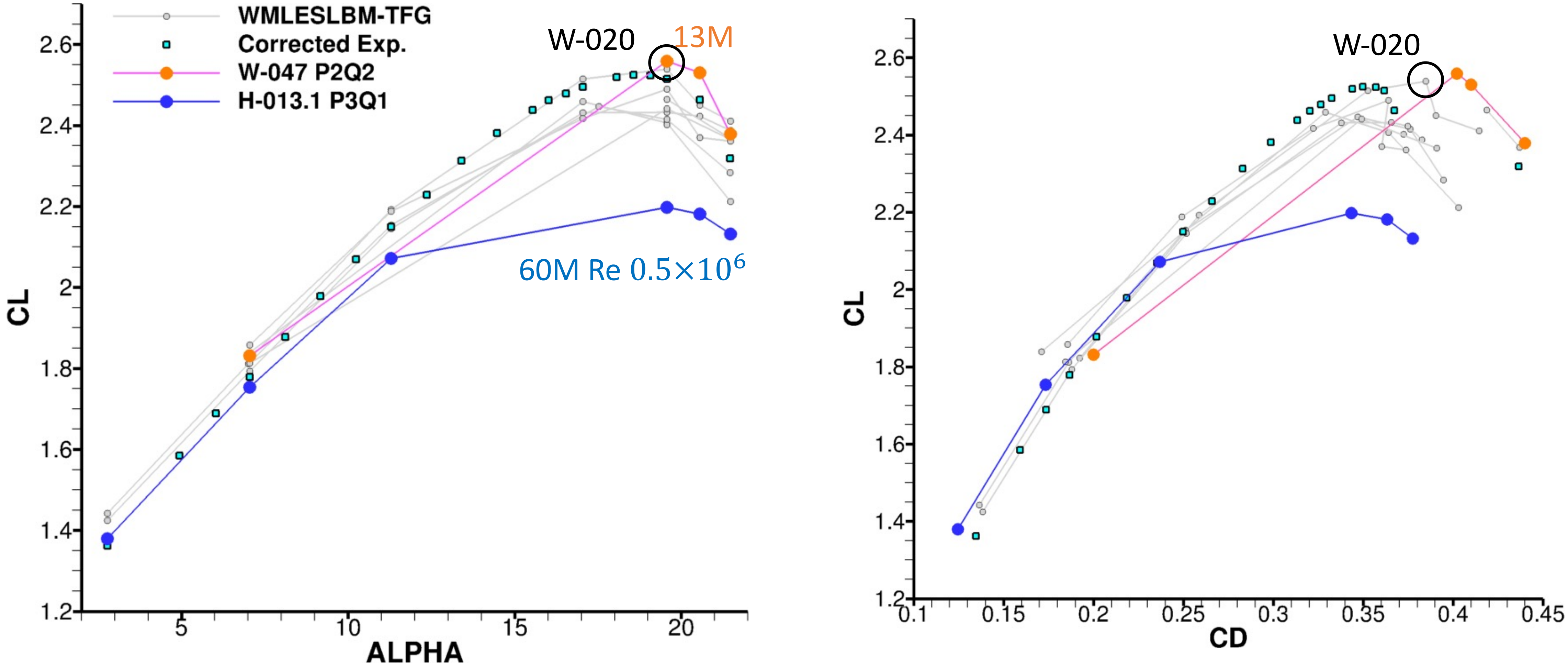


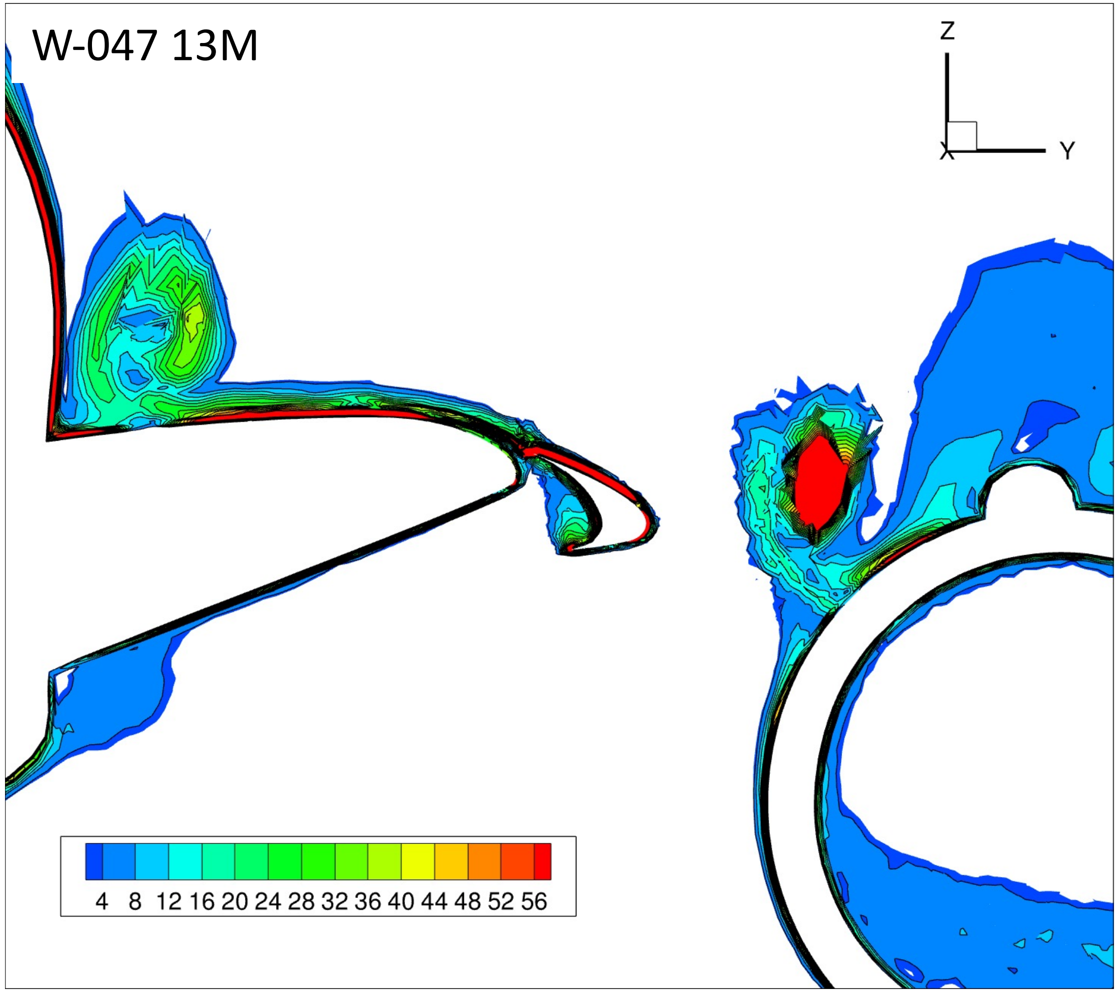


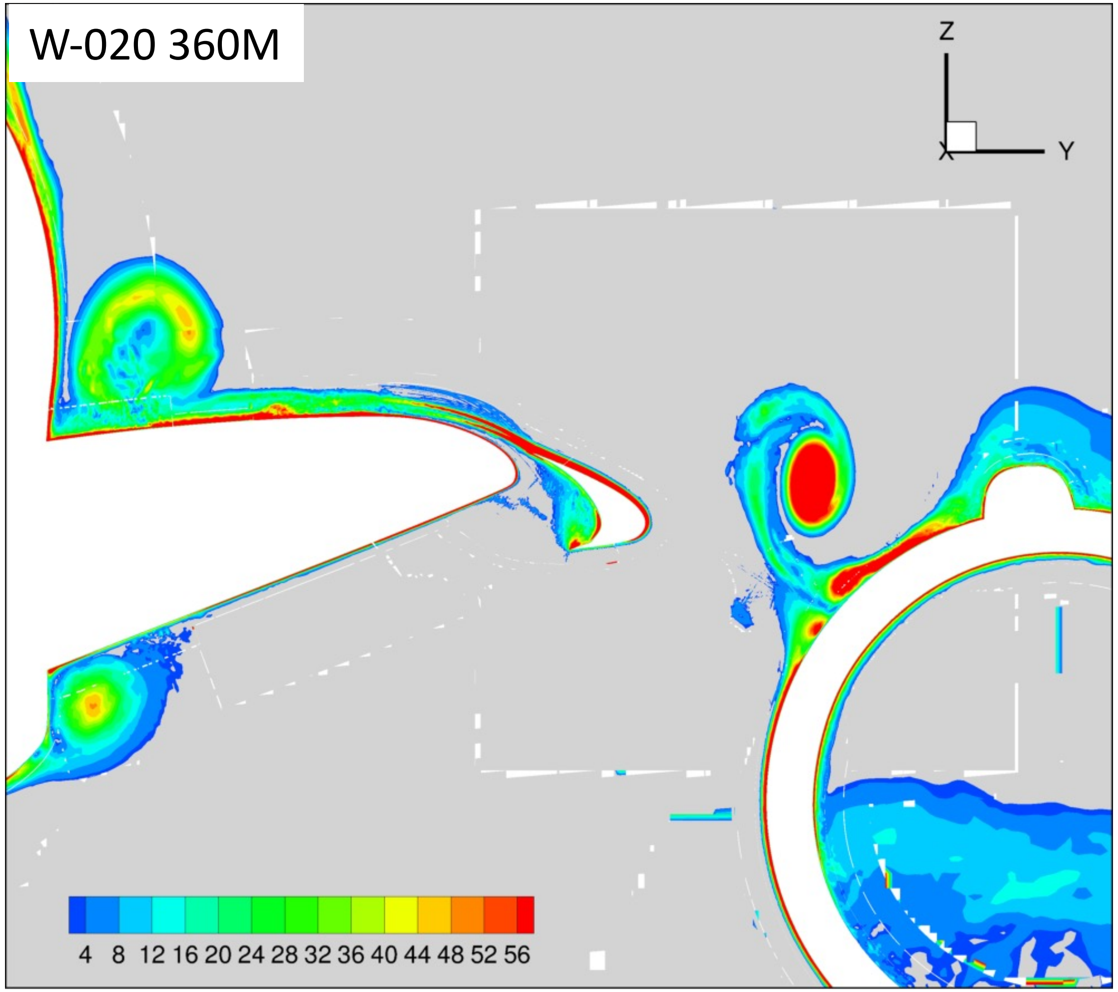
Basic CFD Results Case2a

Lift curve (CL-α), drag polar (CL-CD): LES



WMLES (19.57 AoA) View 11





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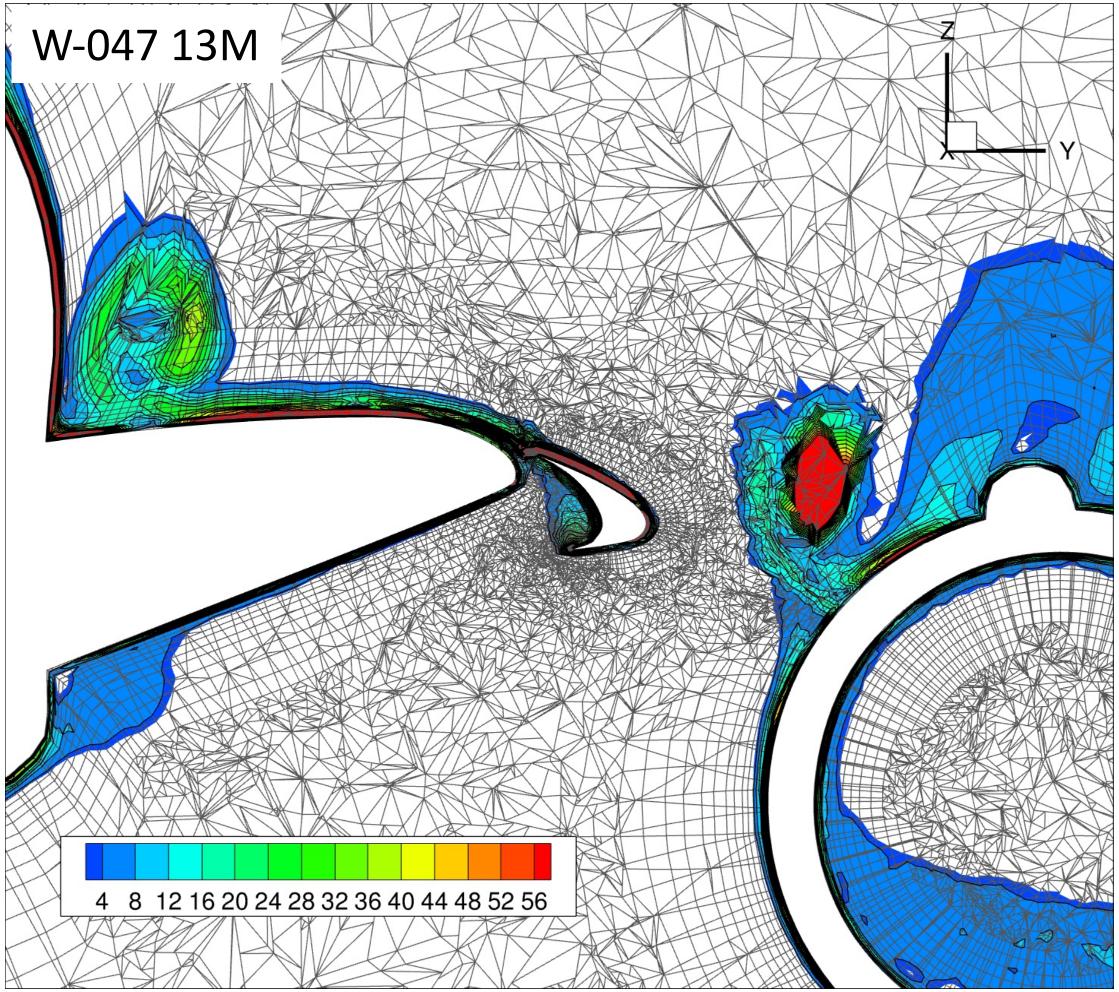
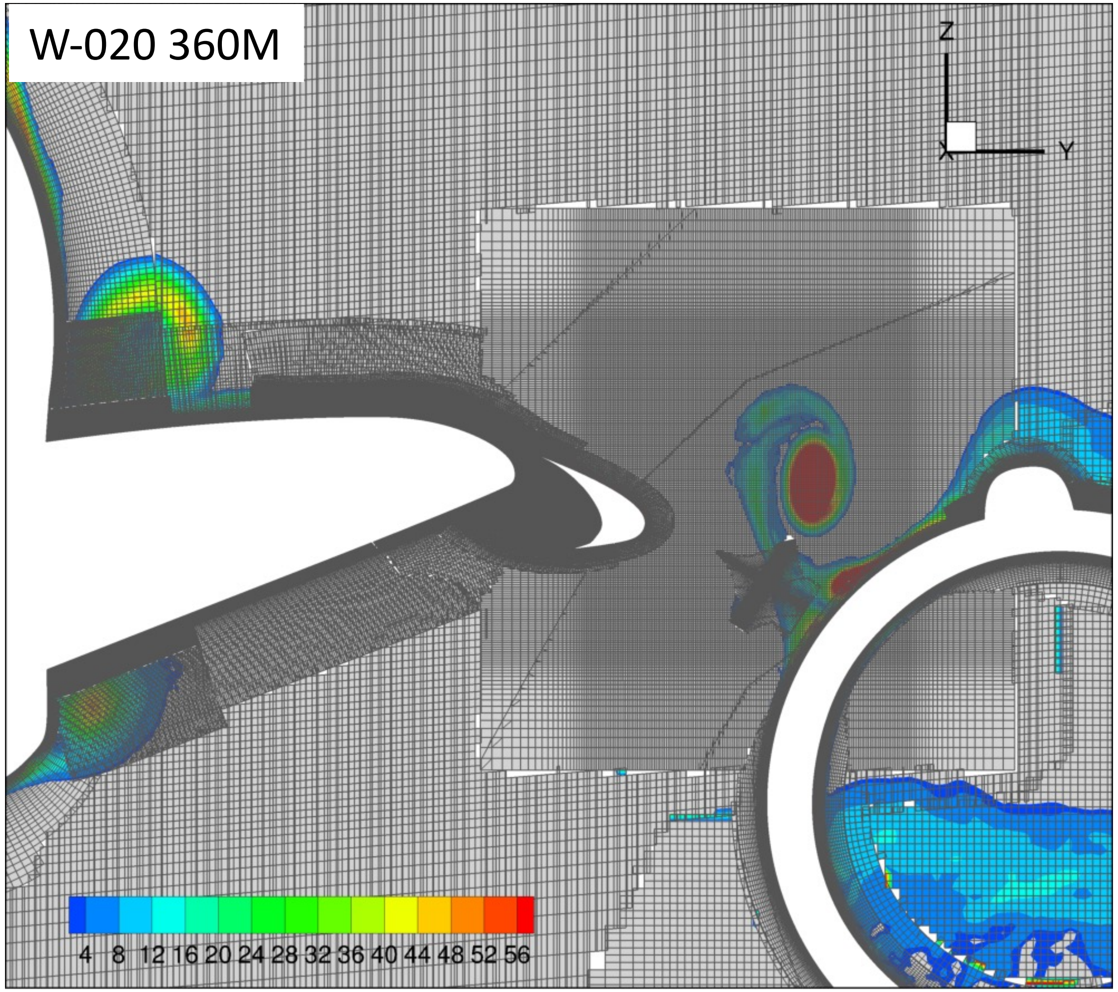
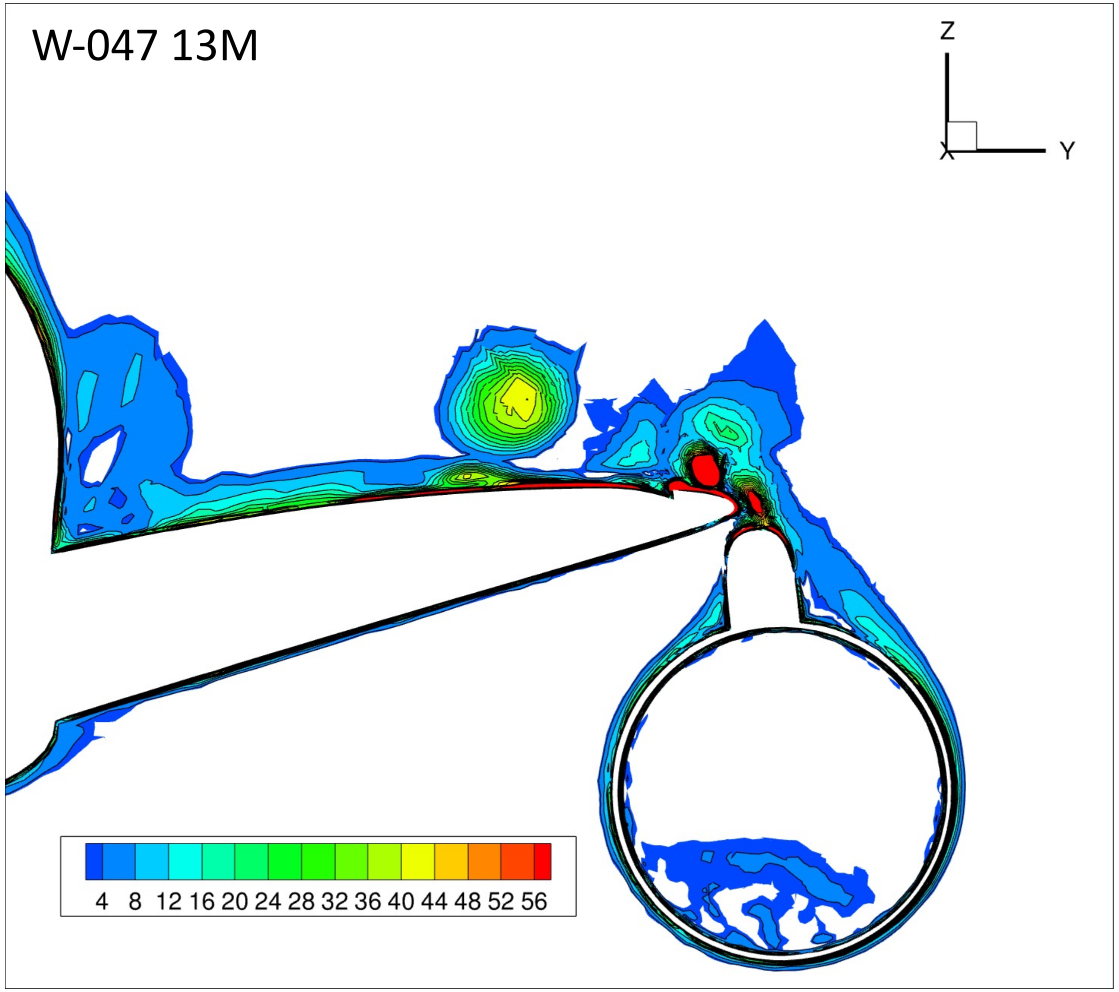
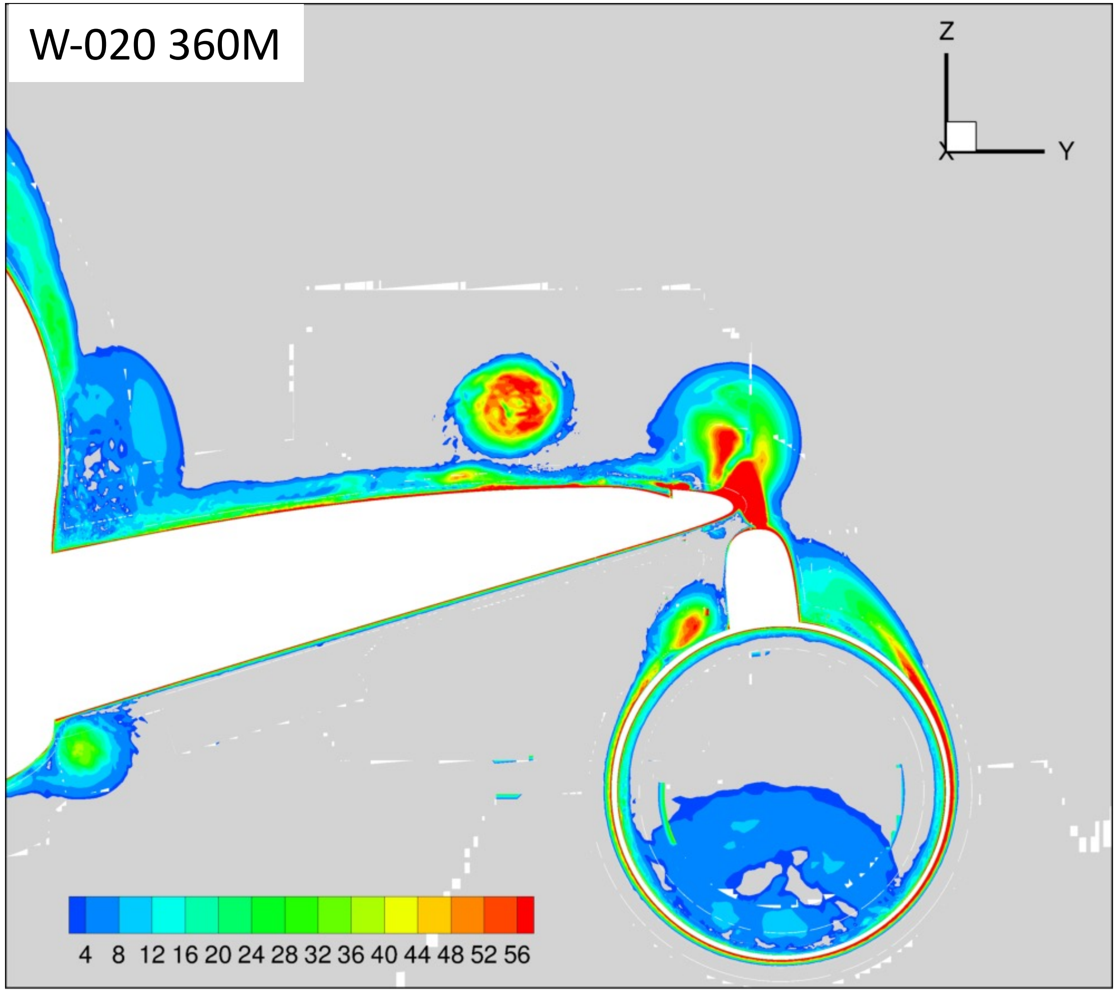




WMLES (19.57 AoA) View 12





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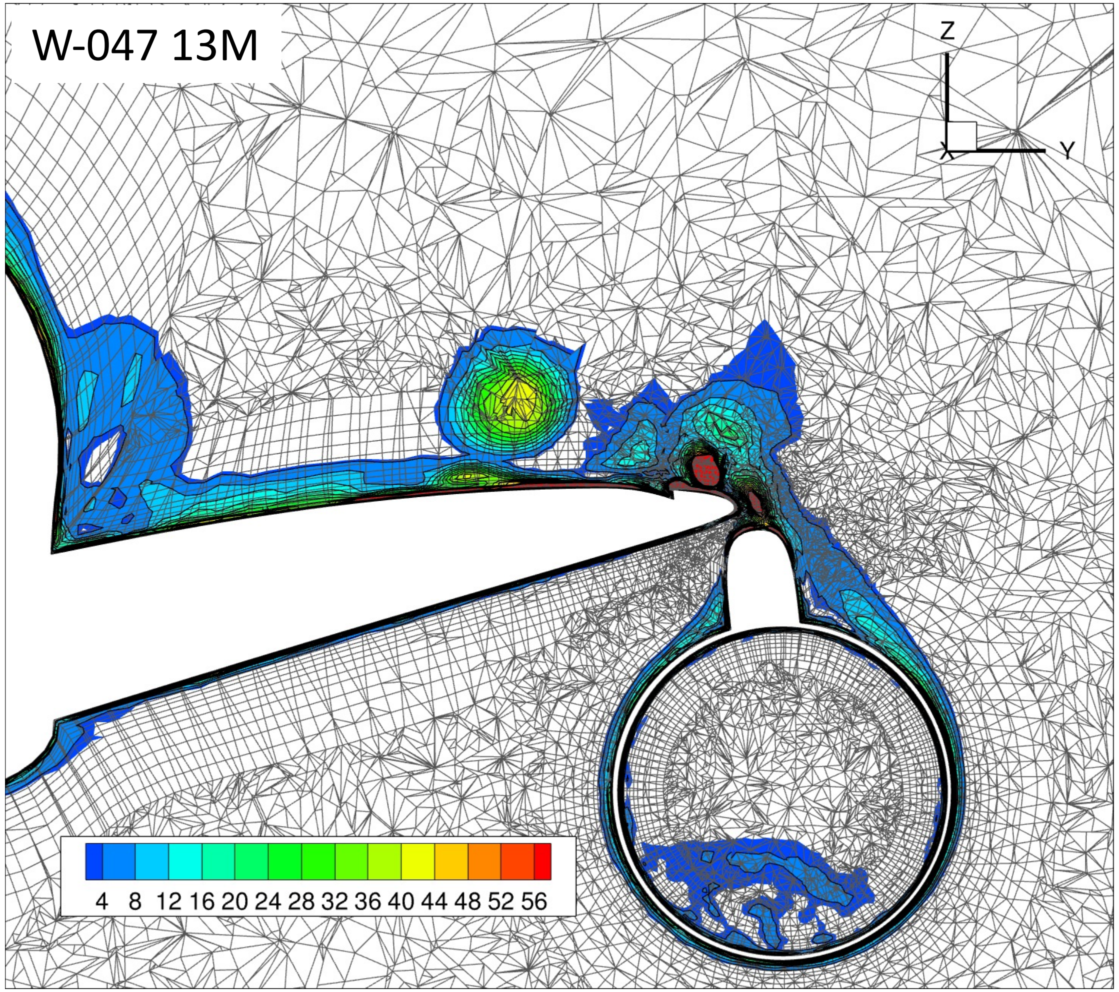
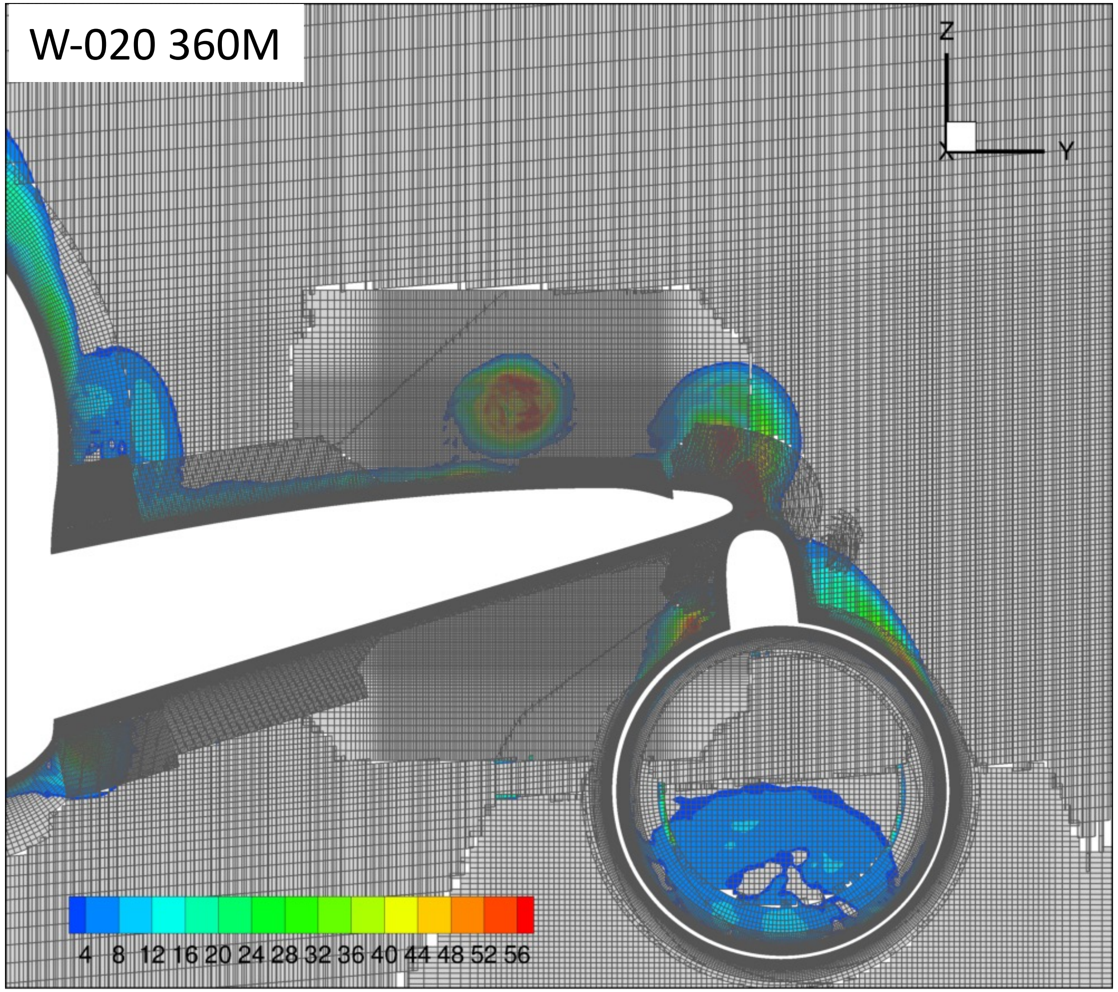
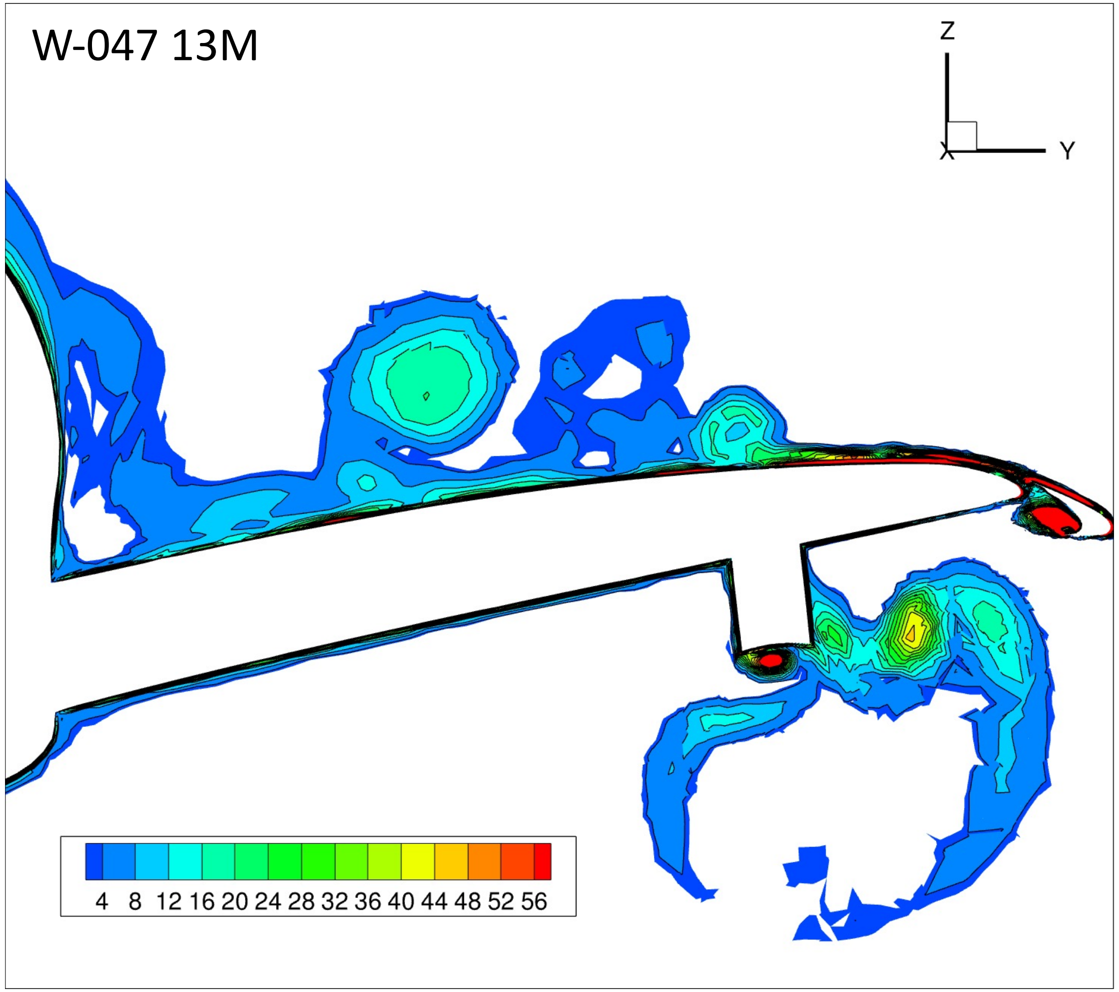
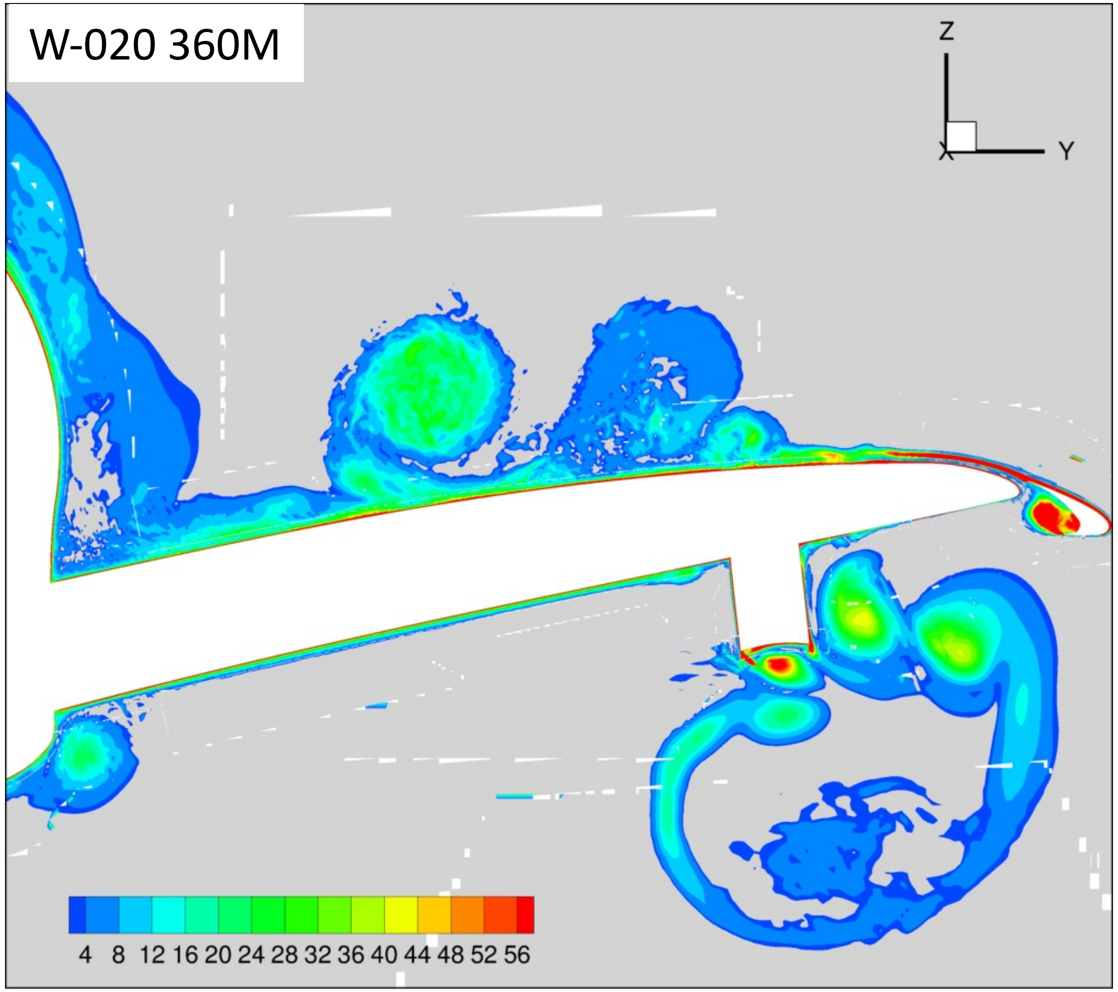


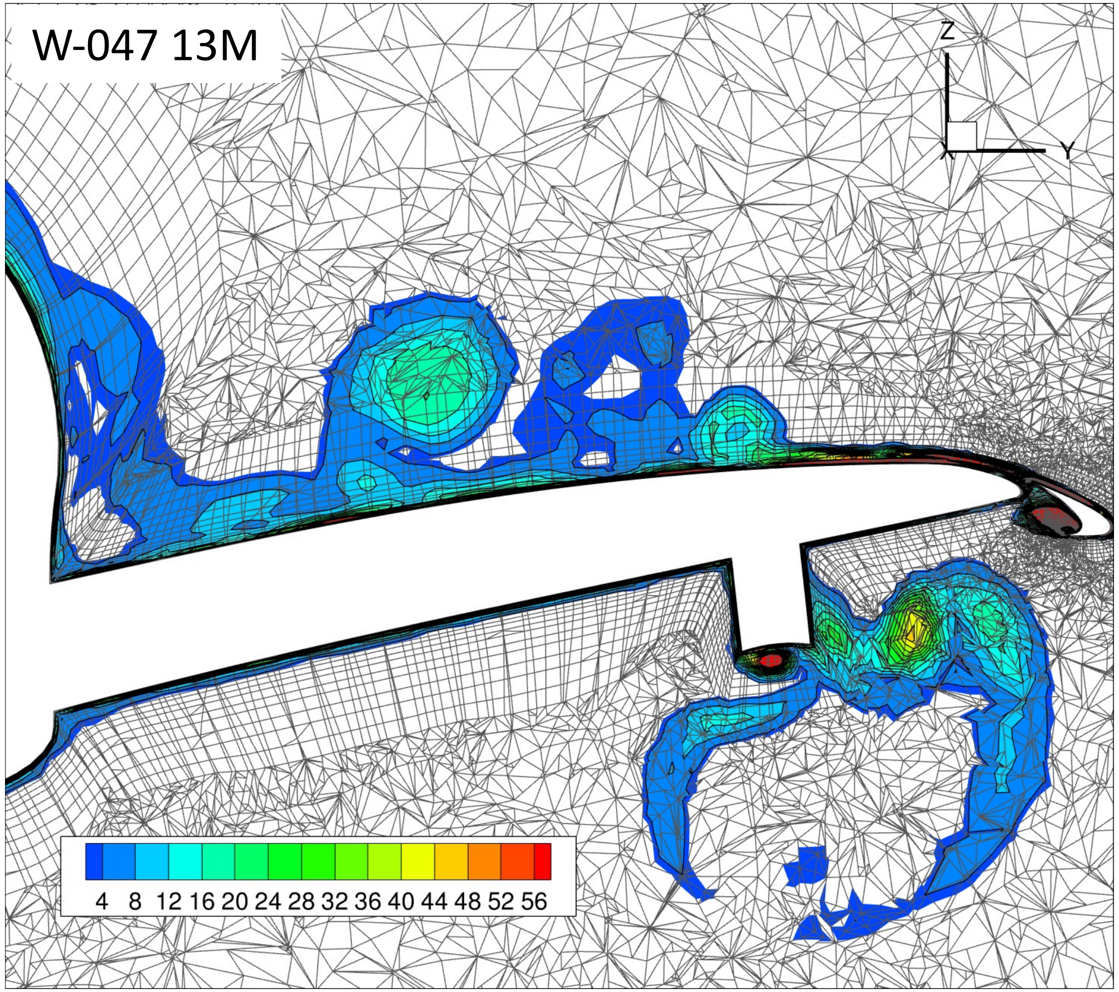


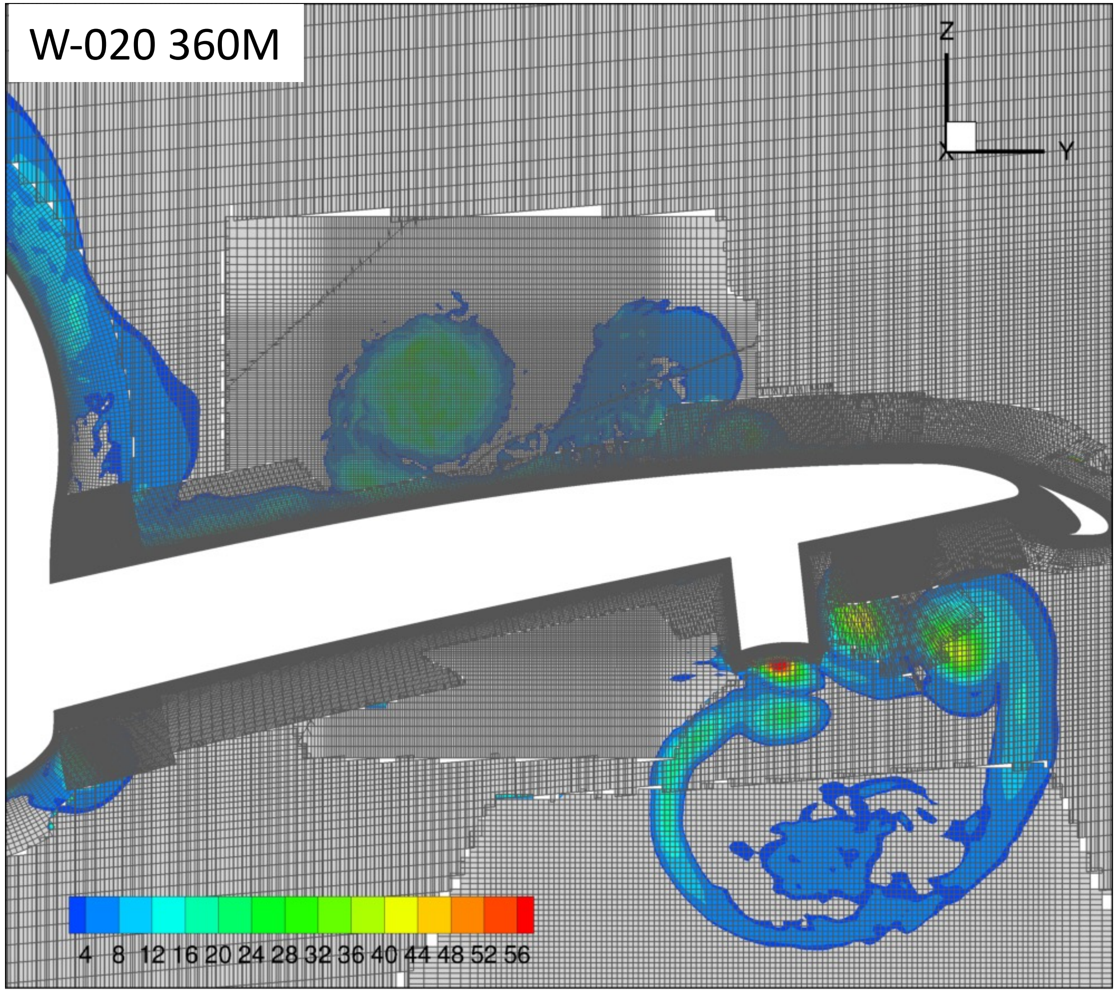
WMLES (19.57 AoA) View 13



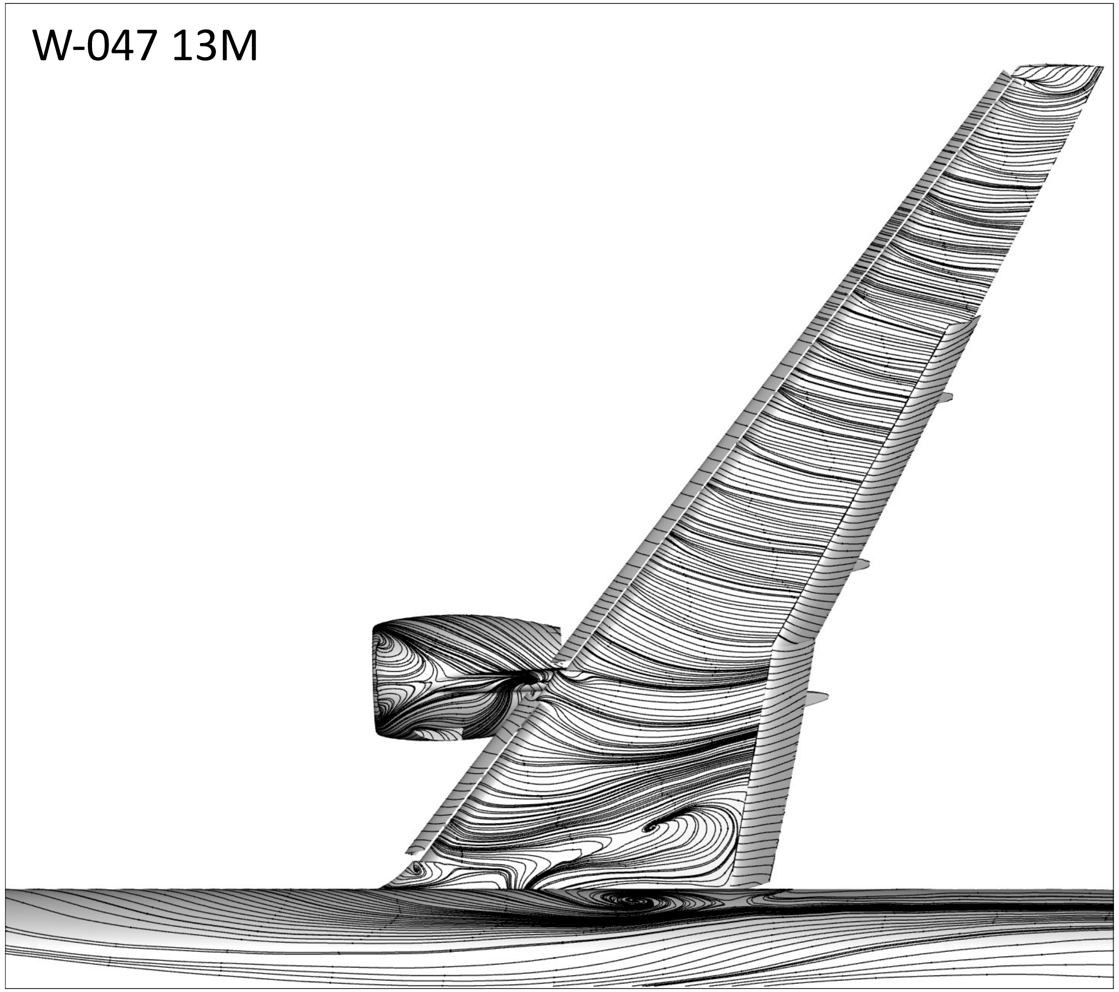


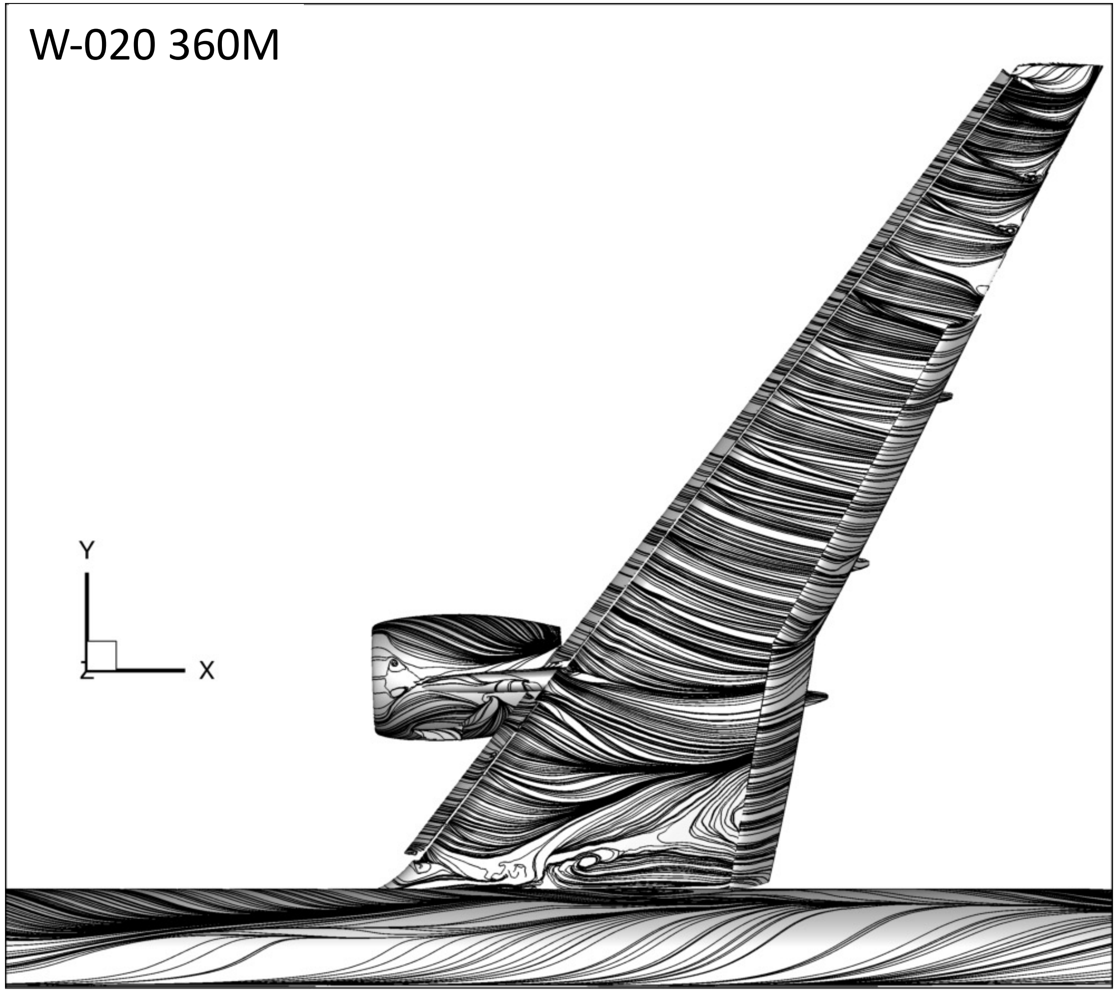
WMLES (19.57 AoA) View 13



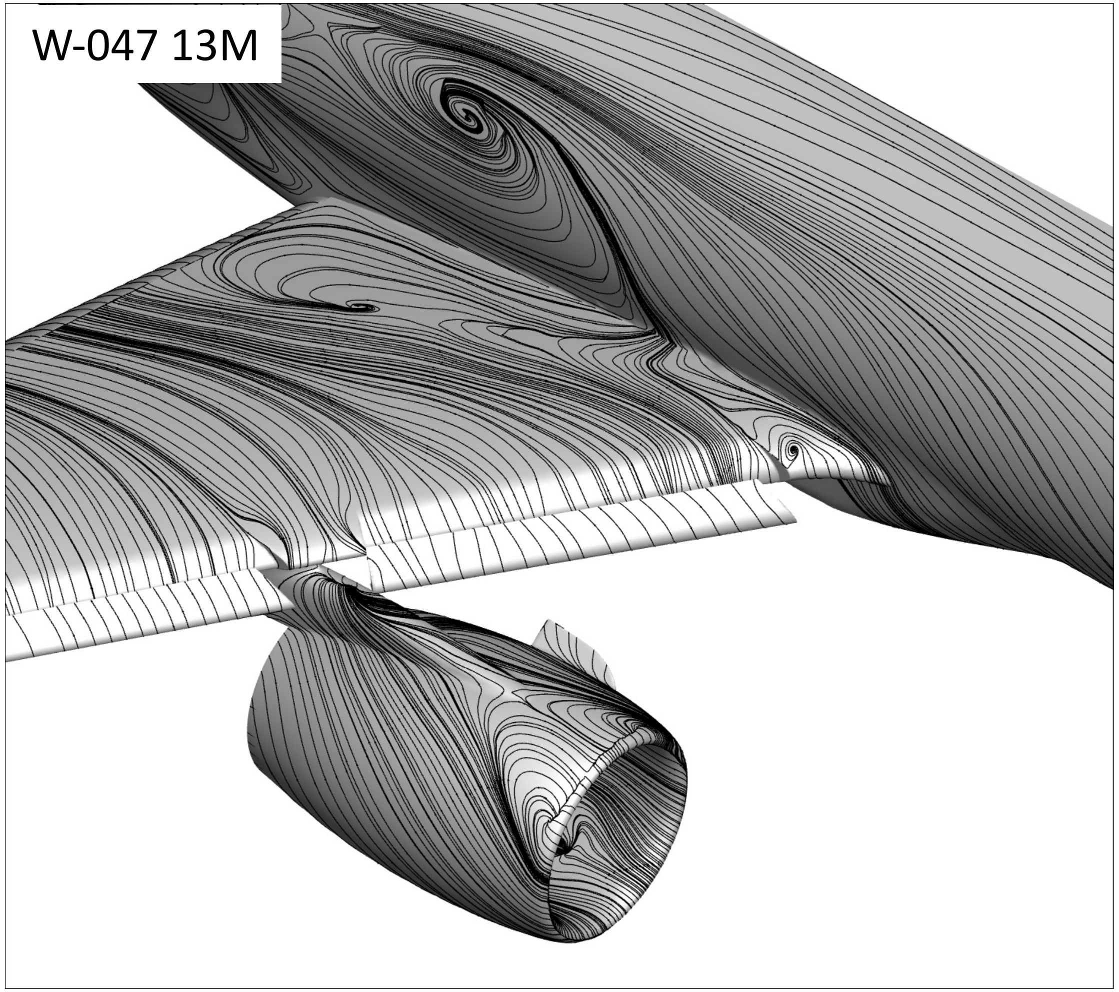


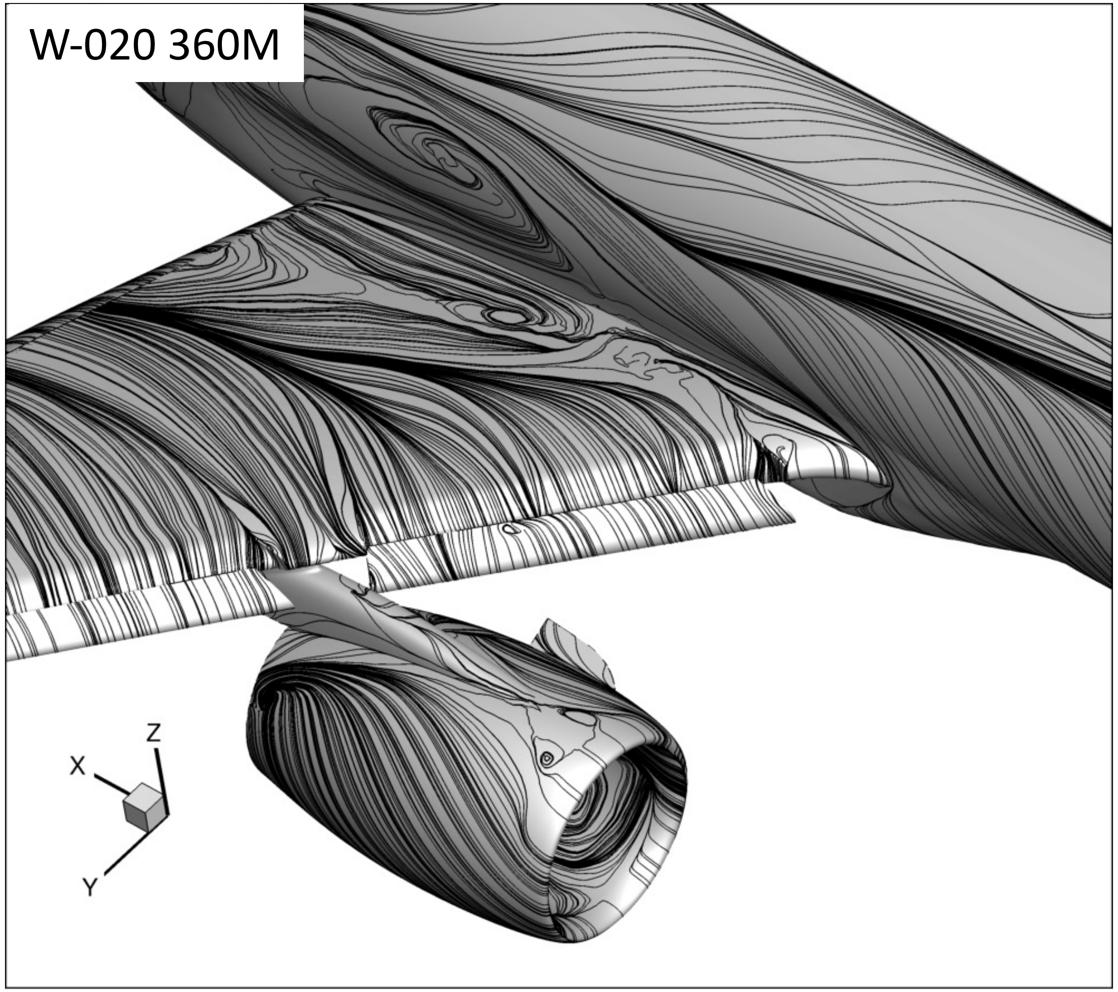
WMLES (21.47 AoA) View 01





WMLES (21.47 AoA) View 05

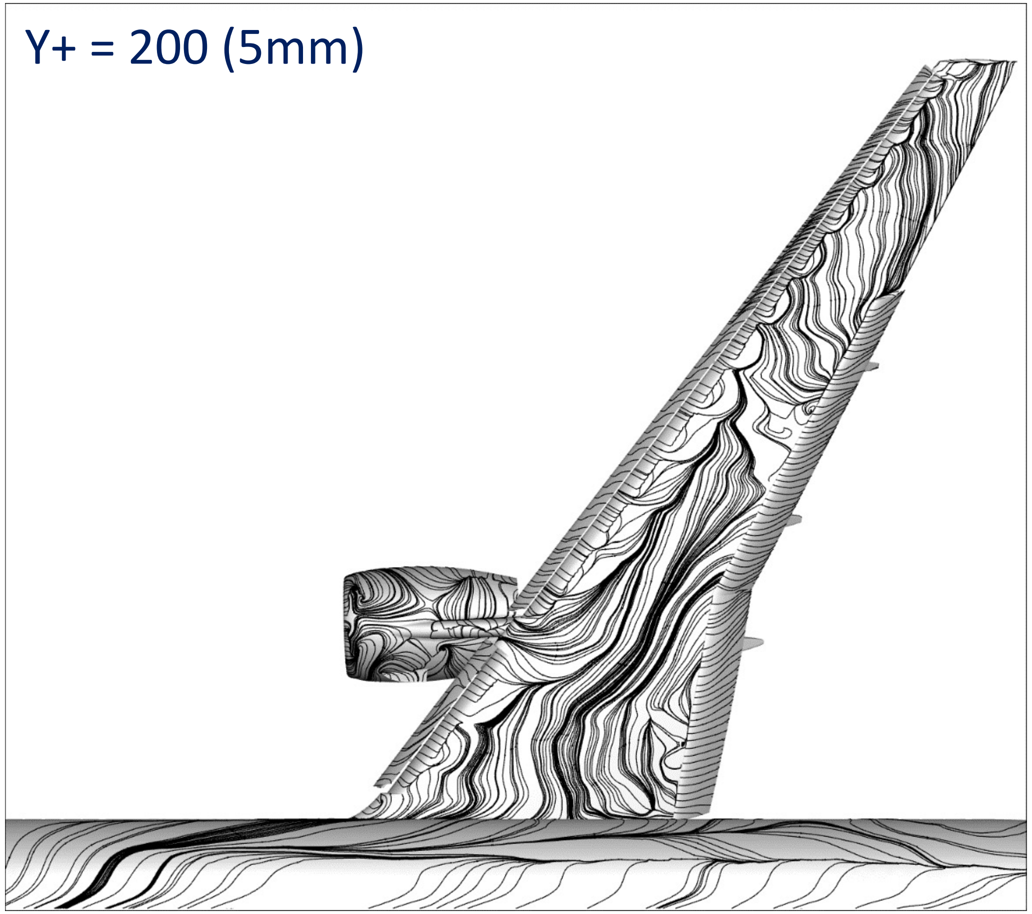


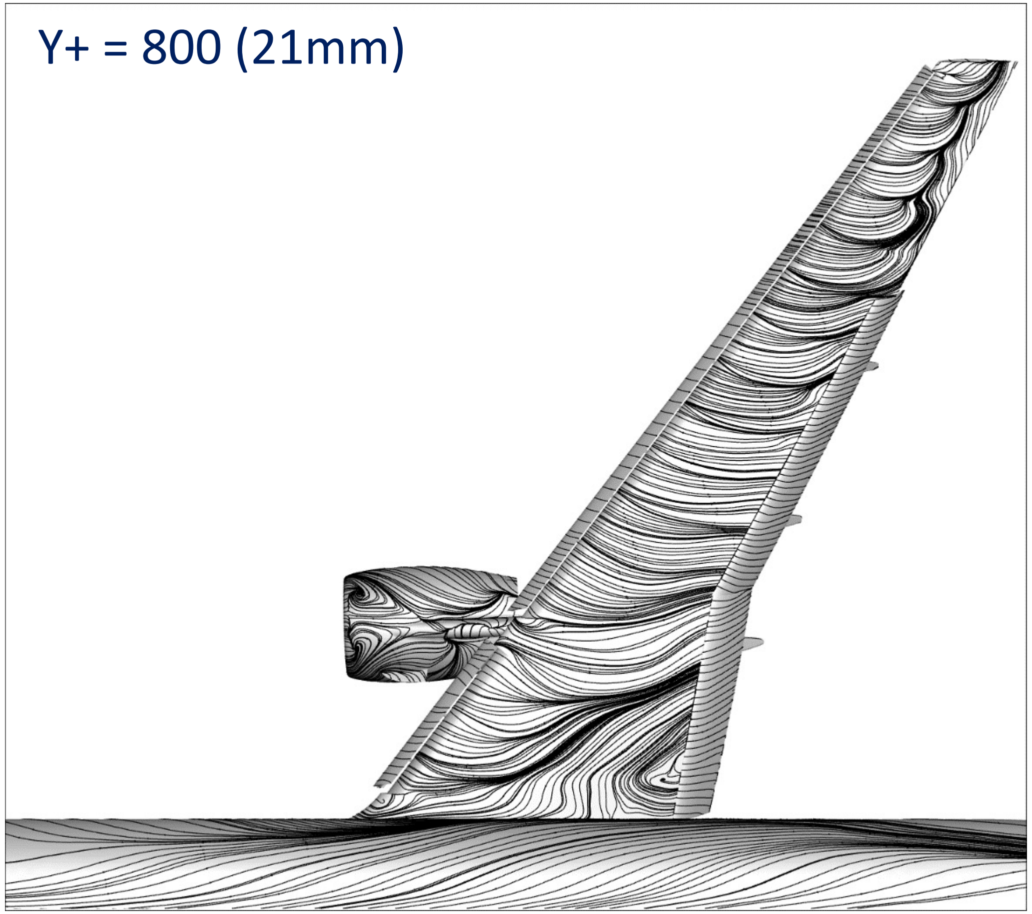


W-047: (21.47 AoA) Oil-flows between Y+ = 200 (5mm) and Y+ = 800 (21 mm)

Same numerical setting at P2

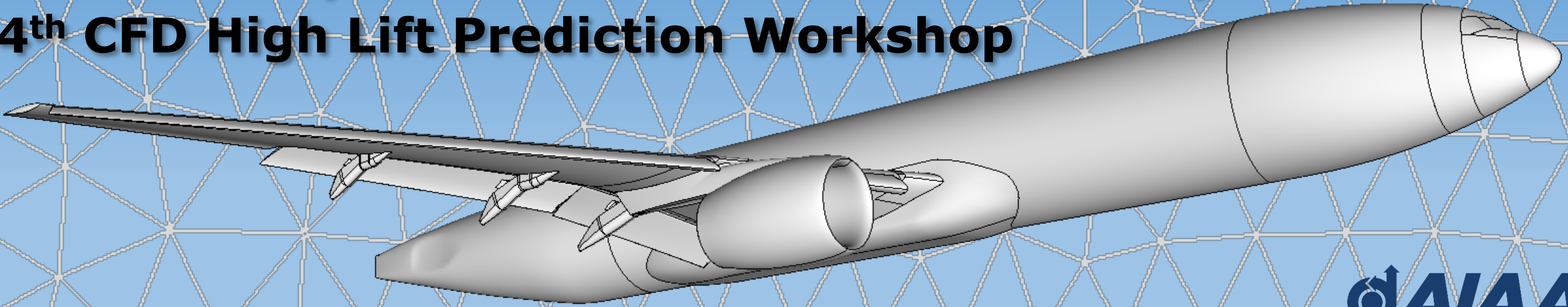
Wall model data extracted between 1st and 2nd element off the wall





Conclusions

- Higher order FEM/FV can be applied to HLCRM
  - Challenging, but doable
  - Mesh exchange issues
- Lots of learning for tuning linear solver settings, time steps, startup procedures (use explicit filtering)
- Implicit solvers are critical for high-order
  - Both RANS and LES calculations
- Mesh adaptation with high order promising in 2D
  - Mesh curving in 3D for highly-anisotropic elements is challenging
- WMLES P2 lift reasonable with only 13M DOF
  - Sensitive to wall element aspect ratio

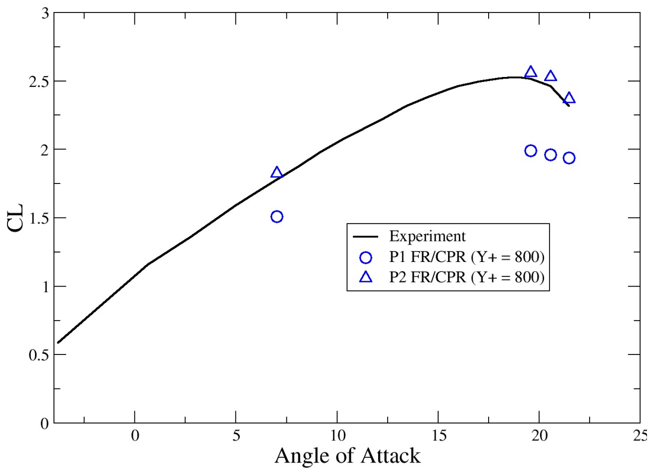


Backup

High-Order LES Case2a

W-047

- P1 and P2 FR/CPR
- Optimized BDF2 with a GMRES solver
- Equilibrium wall-model
- Implicit LES
- Q2 mesh of 1.02M mixed (Pointwise Y+ = 800)
  - P2 ~13.2 M DOF
  - Equivalent Y+ ~ 200-260 near the wall (~7mm)



H-013

- P3 DG
- BDF2 in time
  - Jacobian-free Newton-Krylov ILU(0)-GMRES
- No wall model
- Implicit LES (dt = 4.5e-5)
- Q1 mesh 3M tet (Pointwise Y+ = 100)
  - P3 60M DOF
- Re 0.5×10^{6}